CONSULTANT REPORT

AN ANALYTICAL FRAMEWORK TO EVALUATE THE SUSTAINABILITY OF TRANSPORTATION FUELS

Prepared for: California Energy Commission

Prepared by: TIAX LLC

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PREFACE

TIAX was tasked to conduct this work and prepare this report under Agreement 600-07-008, Task 1.B and Task 3. This report refines and updates the full fuel cycle analysis emphasizing sustainability factors to evaluate plausible transportation fuels identified in the *AB 1007 State Alternative Fuels Plan*.

ABSTRACT

The California Energy Commission has been charged with considering sustainability concerns in the evaluation of projects seeking financial assistance from the Alternative and Renewable Fuel and Vehicle Technology Program, created by Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007). In this report, TIAX's objective was to develop an analytical framework to evaluate the sustainability of transportation fuels. Sustainability is an interdisciplinary concept that considers competing environmental, economic, and societal goals, with the goal of optimally integrating these competing interests. The scope of the report is limited to environmental sustainability, focusing on four specific areas: water resources, water quality, soil quality, and biodiversity. The authors provide an overview of each sustainability consideration based on a thorough literature review, including the current state of knowledge and a summary of metrics that can be used to evaluate the sustainability of transportation fuels. The authors also provide specific recommendations and guidance to advance the goal of developing an analytical framework to evaluate the sustainability of transportation fuels, including guidance in areas such as comparative basis, determination of boundary conditions, identification of data to compile reference cases, and the use of weighting factors. The most striking theme from the research into each of the areas of impacts is the importance of local and regional conditions. Notably, this represents a significant shift from the analytical approach to evaluate the global warming impact of transportation fuel production pathways.[1] In the case of water resources, water quality, and biodiversity, the authors recommend an approach that 1) characterizes local and regional issues or concerns and 2) accounts for a pollutant of concern using an analytical metric. In the case of soil quality, the authors' recommendations are similar, however, they focus on 1) identifying land management practices and 2) determining a soil sustainability index based on a collective or simultaneous consideration of these practices.

Keywords: Sustainability, transportation fuels, lifecycle analysis, full fuel cycle analysis, water resources, water quality, soil quality, biodiversity, climate change, air quality, framework development

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1 A fuel pathway includes the supply chain of each fuel leading up to its use in a vehicle. These steps vary by fuel type, but generally are feedstock, processing or refining, transport, and local distribution.

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EXECUTIVE SUMMARY

Introduction

California is confronting the risks of climate change caused by greenhouse gas emissions, highlighted by the landmark Global Warming Solutions Act of 2006 (Assembly Bill 32, Núñez and Pavley, Chapter 488, Statutes of 2006). The transportation sector in California is a major contributor to greenhouse gas emissions (~40 percent of the state's total annual emissions) and is dominated by petroleum-based fuels (gasoline and diesel), of which California consumed about 18 billion gallons as recently as 2008. In keeping with its tradition of tackling environmental pollutants from the transportation sector, California has targeted both vehicles and fuels to reduce greenhouse gas emissions. On the vehicle side, the Pavley regulations (AB 1493, Pavley, Chapter 200, Statutes of 2001) were enacted to reduce tailpipe GHG emissions for vehicles and the Low Carbon Fuel Standard (LCFS) requires a reduction of 10 percent of carbon intensity of transportation fuels by 2020.

In addition to these regulatory standards, California developed the *State Alternative Fuels Plan* (AB 1007 Pavley, Chapter 371, Statutes of 2005) to address both climate change and petroleum dependence, while prohibiting any back-sliding on air quality. The *State Alternative Fuels Plan* called for significant public investment to enable market transformation for transportation fuels. The Legislature responded by enacting Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007), which created the Alternative and Renewable Fuel and Vehicle Technology Program to make public investments in the alternative fuels market.

The statutory language of Assembly Bill 118 expanded the scope of fuel production pathways – or lifecycle analyses – of transportation fuels to include sustainability considerations. The questions raised by sustainability are far-reaching: What are the impacts of alternative transportation fuels on water resources or water quality? How will food prices be affected by increased biofuels? How will electricity providers meet the increased demand as a result of electric vehicles? What is the transition from conventional natural gas – a fossil fuel – to renewable biogas? These types of questions have no simple answers and reflected a lack of tools to help understand these issues.

Purpose

This report develops a model – or analytical framework – to evaluate the sustainability of transportation fuels. This effort is part of a larger focus of the Energy Commission to refine and update the lifecycle analysis of transportation fuels. Due to the broad range of issues that can be incorporated into a sustainability framework, TIAX worked with the Energy Commission to narrow the scope of this report; the authors focus exclusively on the environmental aspects of sustainability. More specifically, the authors researched the lifecycle impacts of transportation fuels on water use, water quality, soil quality, and biodiversity. The selection of these impact areas for further research is not meant as a marginalization of other aspects of sustainability, but rather a reflection of the need to prioritize Energy Commission efforts based on limited time and resources.

Objective

The challenge of developing an analytical framework for sustainability considerations of transportation fuels is that there is not much precedent in this area. To date, sustainability has largely been assessed on a *qualitative* basis rather than an *analytical* basis. This is an important distinction because it frames the problem in a decidedly different fashion. The analytical aspect of sustainability suggests an emphasis on basic principles. In other words, the discussion of sustainability as a holistic approach that reflects environmental, economic, and social concerns has limited use in developing an analytical approach. The authors' approach must separate and break down the sustainability impacts into their constituent parts and variables. For instance, in each of the areas of impact – water use, water quality, soil quality, and biodiversity – there is a qualitative understanding of what is "good": Don't use too much water, don't pollute waterways, don't pollute the soil, and maintain or improve biodiversity. The approach here is to break down those qualitative and, in some cases, quantitative measures into variables and parameters that can be measured to differentiate between the bad, the good, and the better of the unsustainable and sustainable.

Another objective of this work is to help differentiate among fuel options over a number of considerations simultaneously, rather than one issue at a time. In other words, the metrics used to determine performance should apply across fuels and establish a consistent approach. The fuels to which the framework should apply include gasoline and diesel, biofuels (ethanol or biodiesel), natural gas (compressed and liquefied), electricity, and hydrogen. Fuel production pathways (feedstock, refining, transport and local distribution) will have varying degrees of impact in the areas of interest – water use, water quality, soil quality, and biodiversity – but, in principle, the measures (metrics) employed should be applicable to the entire spectrum of transportation fuels.

As part of the literature review, TIAX developed analytical criteria to guide this research. The objective of these criteria is to ensure that the metrics and variables considered within each area of impact are valid and appropriate for consideration in an analytical framework (hypothetical model) to assess the sustainability of transportation fuels. TIAX developed the following criteria.

1. The impact(s) must be measurable, quantifiable, and verifiable. In each area, the authors must consider whether the impacts are developed using data that can be measured in the field. If data cannot be measured, then models can be employed; however, the data that are generated from modeling must be explicitly identified as such. The impacts must also be verifiable. The verification of impacts includes a coming together of factors such as peer-reviewed data, public accessibility, transparency, and clearly identified boundary conditions, which set the limits and define the elements of the fuel production pathway included in the analysis. The verification requirement is a quality assurance and quality control mechanism.

2. There should be a reasonable degree of consensus regarding the approach to quantify the impact(s) in question, and there should be agreement regarding the usefulness of the related metrics. The authors seek an approach that has a reasonable degree of consensus among experts in the corresponding field. The framework proposed has a number of cross-cutting themes. As such, it is important that the approach to quantify the impact(s) is consistent with the level of knowledge in the corresponding field. In addition to consensus in the various research fields regarding the approach, the authors hope to identify variables and metrics that are most useful in assessing sustainability impacts.

Based on the objectives outlined above, each area of impact includes a discussion of the following:

- **Review each area of impact** and provide a basic overview of the area considering its importance in the context of sustainability. The authors provide the definition of what is considered in this report, and, where appropriate, they discuss how and why the definition is similar to or different than what is used elsewhere.
- **Assessment of the current state of knowledge** based on the authors' literature review.
- **Identify the metrics used for each area of impact** where appropriate. These metrics are evaluated in the context of the review criteria that the authors have outlined in Chapter 2.
- **Suggest how the data could be incorporated into a framework** to assess the sustainability of transportation fuels. This section includes the following:
  - **Discuss appropriate comparative basis**. The purpose of this section is to discuss ways to develop a method that considers marginal and average impacts separately and ensures that the comparison is done on an equivalent basis.
  - **Discuss boundary conditions.** To date, the focus of lifecycle impacts of transportation fuels has focused on GHG emissions, which are considered uniform across space. The local and regional conditions that affect water use, water quality, soil quality, and biodiversity make it more challenging to incorporate these issues into an analytical framework.
  - **Identify data to compile for reference cases.** The development of an analytical tool to evaluate the sustainability of transportation fuels will require the development of reference cases. The authors identify the types of data and variables that will need to be inventoried to develop appropriate reference cases.
  - **Discuss weighting factors.** Weighting factors are generally subjective and are reflective of value judgments based on policy goals. Many of the areas of impact that TIAX investigated will require a composite of indices or the simultaneous consideration of several variables. Although it is beyond the authors' scope to quantify weighting factors, they identify the key variables and discuss their relationships. The authors also identify what they consider as potential pitfalls associated with some variables, as appropriate.

Conclusions and Recommendations

The most prominent theme from this research into each of the areas of impacts is the importance of local and regional conditions. This represents a significant shift from the analytical approach to evaluate the global warming impact of transportation fuel production pathways. The accounting of energy inputs and outputs in the fuel production pathways, although challenging, is comparatively straightforward. This is due in large part to the global nature of climate change.

Despite the localized nature of each area of impact, TIAX has developed recommendations for the development of a framework in each case. In the case of water resources, water quality, and biodiversity, the research team recommended a twofold approach that can be generally described as follows:

- Define the local/regional impacts as a stress or health index at each stage of the fuel production pathway.
- Define a variable, or set of variables, that are measureable (in the field or laboratory) and quantifiable (using models or simulation) to characterize the effects on the area of interest.

The recommendations for soil quality are in the same mode of thinking; however, they focus on land management practices. Land management practices are driven by local and regional impacts, which are consistent with the other areas. The difference is that land management practices for soil quality associate strongly with existing metrics, which limit the usefulness of the second step listed above. Rather, the second step in developing the soil quality framework is to determine how the evaluation of land management practices is to be aggregated. For instance, the framework may include the development of a single soil sustainability index, or the land management practices could be considered separately. In either case, the spirit of the second step is to provide an analytical solution to evaluate the impacts of transportation fuels on soil quality.

It is difficult for TIAX to conclude what the relationship between the two steps for each area will be without actually developing the framework. However, as the framework is developed, the authors are confident that the appropriate combination of these two steps will be apparent. Generally, the following factors must be considered for each area of impact:

- **Develop baseline activities for each area of impact**. On what common basis can fuel production activities be compared?
- **Determine temporal (time) and spatial (space) boundary conditions** for each area of impact along the entire fuel production pathway. What components of the fuel production pathway are included in the assessment of sustainability impacts? Which historical conditions or estimated future impacts should be considered? What physical boundaries should be included?
- **Establish inventory of data** to evaluate effects of fuel production pathways. What are the practices relevant to the fuel production pathway, and how do they affect each area of sustainability?
- **Determine weighting factors** for evaluation purposes. To what degree does each pathway affect sustainability, in terms of metrics, value judgments, and policy goals?

Combined, these steps will move the framework for sustainability toward a robust and useful evaluation tool that reflects key sustainability goals.

Water Resources

There is a high level of understanding of the water consumption requirements of transportation fuels, particularly at the farm level, where they are most important. These data, however, must be integrated with local and regional conditions, such as water availability, water pricing, and crop substitution.

The twofold approach for water resources and next steps include the following:

1. **Determine local/regional water stress indices that quantify the imbalance between available water resources and water use**. The Energy Commission should become familiar with the WaterGAP2 model, including its strengths, limitations, and ongoing development. There may also be other water stress indices[2] used by local and state water agencies in California or around the United States, particularly in other states with high agricultural outputs.
2. **Use a Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) type format/model to track other variables and parameters** such as: water requirements, crop type, local/regional climate conditions, soil type, soil quality, and water cooling requirements.

Water Quality

As in the case of water consumption, the knowledge base for the impacts of farm production practices and refinery processes on water quality is solid. However, the data requirements to develop a framework to evaluate transportation fuels are intense. The extensive knowledge base for water quality impacts from various fuel production processes must be coupled with a local or regional watershed modeling effort. This effort, however, may be prohibitively time- or resource-intensive. As an alternative, the Energy Commission could investigate the usefulness of coupling the water pollutant use with water quality indicators to get a better understanding of the potentially sensitive areas in California and beyond, which would lead to unhealthy and unsustainable water quality impacts.

1. **Characterize the local and regional issues of water quality**. The authors present two suggestions or recommendations to complete this step.
    a. In the first option, the authors refer to a guidance document for the development of site-specific water quality objectives published by the California State Water Resource Control Board (SWRCB 2003). There are similar resources available at the federal level from the EPA.
    b. The other option is to perform local and regional watershed modeling. This option is likely more intensive but probably more rigorous and robust. This option is analogous, for instance, to air shed modeling that is performed in air quality studies.
2. **Account for pollutant discharge at each stage of production using a GREET-type format/tool**, which would be aggregated and reported on a per unit energy of fuel basis.

2 Water stress indices are indicators that measure the stress caused by the imbalance between available water resources and water use.

Pollutants to consider include fertilizers and pesticides, herbicides or fungicides for farm production; total dissolved solids and other refining effluent.

Soil Quality

The existing knowledge base for soil quality and land management practices through academic research and actual practice is strong. Specific additional research is likely not needed to bridge soil quality and an analytical framework. However, much work remains to be done in making decisions regarding the relative value of the various soil quality parameters in evaluating sustainability. With these considerations of relative value to various stakeholders, the authors recommend the following two-step approach:

1. **Identify the most pertinent land management practices that reflect impacts on soil quality.** A framework based on land management practices reflects the relationship between an activity and its effects on soil quality indicators without requiring the direct and ongoing comparison of soil sample measurements. The aim of this framework is to distill out the key drivers of soil quality; even if a particular metric is not specifically addressed, its role in soil quality should be captured and indirectly represented by the set of land management practices.
2. **Develop a composite index based on land management practices.** To use the framework, the evaluator determines how the activity applies to each of the identified land management practices. The individual scales for these practices can then be assessed separately or collected into a soil quality index for comparison with other activities.

Biodiversity

The existing knowledge base for biodiversity, as it is affected by fuel production, is the weakest of all the area of impact in this report. The emphasis on biodiversity is based solely on the assumption that biodiversity is important. In other words, there is a binary choice: a high level of biodiversity is good, whereas low-to-no biodiversity is bad. Furthermore, biodiversity is extremely complex and is a function of many variables, including, but not limited to, the other areas of impact considered in this report (water use, water quality, and soil quality). Biodiversity is an active area of research; yet there is still not a clear connection between biodiversity and ecological function. Despite the complexity of the task and data limitations, the importance of preserving biodiversity is without question. To develop a framework to evaluate the sustainability of transportation fuels without considering biodiversity would be a gross oversight.

The authors recommend the twofold approach, similar to the one proposed for water resources and water quality, for biodiversity.

1. **Determine an appropriate composite of biodiversity indices**. Raw data for biodiversity indices are available from various sources (NatureServe, the Global Biodiversity Information Facility, the U.S. Fish and Wildlife Service Threatened and Endangered Species Database System, or the California Natural Diversity Database). It is important to iterate that a composite of indices is required for this step to be relevant. A single metric of biodiversity will not accurately capture the risk posed to a particular region or habitat. More so than other areas, this task should be done in close collaboration with

experts in the field to ensure that the results are applicable and reflective of the current understanding of biodiversity.

2. **Define and characterize variables that impact biodiversity and account for these variables along the entire fuel production pathway.** This task is as much about biodiversity as it is other environmental impacts. This step will require considerable comparison between various metrics to demonstrate how they impact or correlate with biodiversity and how they correlate with each other.

In addition to developing a framework to include biodiversity, further research will bridge the gap between biodiversity and its relationship to the effects on the fuel production pathway.

CHAPTER 1: Introduction

The State of California has a history of confronting difficult issues that cross environmental, economic, and social boundaries. As the major challenges facing California and the United States have evolved, so too have the state's actions to rise to these challenges. Over the last several decades, California's initiatives have followed a logical progression. From initial efforts to tackle air quality issues, the state has complemented these efforts with actions to reduce petroleum dependence and, more recently, curb greenhouse gas (GHG) emissions that cause climate change. As California moves forward, the state will seek to develop a coherent and coordinated approach to deal with the multitude of challenges such as air quality, petroleum consumption, and climate change. The broader use of sustainability is a convenient framework to address existing issues while incorporating other critical concerns simultaneously.

This year marks the 40th anniversary of the California Environmental Quality Act (CEQA), designed to supplement the National Environmental Protection Act (NEPA). The CEQA statute requires that state and local agencies identify the significant environmental impacts of their actions and avoid or mitigate those impacts, if feasible. Around the same time that NEPA and CEQA took effect, the California Air Resources Board set air quality standards for total suspended particulates, photochemical oxidants, sulfur dioxide, nitrogen dioxide, and carbon monoxide. California's population had reached 20 million by 1970, nearly double the population from 1950, and car ownership was increasing significantly. Air quality problems grew as the population boomed and vehicle miles traveled (VMT) increased. Ozone concentrations in the South Coast Air Basin, for instance, were 0.58 ppm, nearly five times the health-based national standard of 0.12 ppm. Since then, the 8-hr standard in California has been reduced to 0.07 ppm. To achieve air quality targets, California adopted aggressive regulatory standards and continued to implement innovative programs for vehicles – on- and off-road, light- and heavy-duty – and transportation fuels to address air quality concerns. On the vehicle side, the state developed programs such as the Zero Emissions Vehicle (ZEV) Program for light-duty vehicles and the Carl Moyer Program for heavy-duty vehicles. On the fuel side, California developed rules for reformulated gasoline and for cleaner burning diesel.

In addition to these air quality issues, California has also sought to reduce petroleum dependence. The Legislature recognized that the increasing consumption of petroleum products – primarily transportation fuels – in the face of limited refining capacity and less secure sources of crude oil exposed the economy to great risk. In 2000, Assembly Bill (AB) 2076 (Shelley, Chapter 936, Statutes of 2000) required the Energy Commission and the California Air Resources Board to develop and submit a strategy to the Legislature to reduce petroleum dependence in California. The strategy highlighted ways to improve vehicle efficiency and introduce alternative fuels to reduce California's petroleum dependences in the near to long term.

More recently, California has confronted the risks of climate change caused by GHG emissions, highlighted by the landmark Global Warming Solutions Act of 2006 (AB 32, Núñez and Pavley, Chapter 488, Statutes of 2006), which uses a combination of regulatory and market mechanisms to reduce GHG emissions. The transportation sector in California is a major contributor to GHG emissions (~40 percent of the state's total annual emissions) and is dominated by petroleum-based fuels (gasoline and diesel), of which California consumed about 18 billion gallons as recently as 2008 (Energy Commission 2010). As was the case with air quality, regulations have targeted both vehicles and fuels to reduce GHG emissions in the transportation sector. On the vehicle side, the Pavley regulations (AB 1493, Pavley, Chapter 200, Statutes of 2001) were enacted to reduce tailpipe GHG emissions for vehicles, and the Low Carbon Fuel Standard (LCFS) requires a reduction of 10 percent of carbon intensity of transportation fuels by 2020.

California has developed a series of policy goals and objectives in the transportation sector to complement regulations and standards. The California *State Alternative Fuels Plan* (AB 1007, Pavley, Chapter 371, Statutes of 2005) is designed to address both climate change and petroleum dependence, while prohibiting any back-sliding on air quality. The *State Alternative Fuels Plan* called for significant public investment to enable market transformation for transportation fuels. The Legislature responded by enacting Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007), which created, among other programs, the Alternative and Renewable Fuel and Vehicle Technology Program to make public investments in the alternative fuels market.

Legislative mandates and regulations have forced California to grapple with the environmental and health problems resulting from the replacement of one environmental pollutant by another. For instance, the toxicity of lead resulted in the introduction of methyl t-butyl ether (MTBE) in gasoline to prevent engine knocking. Subsequently, however, MTBE was banned when it was discovered in elevated concentrations in ground and drinking water. MTBE is particularly dangerous because of its high water solubility and persistence in the environment. By 2003, California switched to ethanol to replace MTBE. The state acknowledged the need to take a broader, systems-level look at the potential effects of gasoline additives and included a legislative requirement for any oxygenate or additive to gasoline (other than ethanol) to undergo a multimedia impact evaluation.

Today, policy makers are drawing from California's history of tackling complex issues and recognizing the importance of examining the broader impacts of various activities. In the *State Alternative Fuels Plan*, ethanol was included as a major component of the proposed strategies to introduce alternative fuels and meet key energy and environmental goals (Farrell, Plevin et al. 2006). Even so, the *State Alternative Fuels Plan* clearly stated that, in the case of biofuels like ethanol, "sustainability issues, such as land conversion and water consumption, still need to be addressed." Concerns regarding indirect land use change and associated GHG emissions peaked in February 2008 when Searchinger et al. (2008) estimated that corn ethanol would lead to an additional 100 grams carbon dioxide (CO_2) equivalent emissions per megajoule of fuel (gCO_2eq/MJ) in addition to the 60-65 gCO_2eq/MJ of direct emissions over the lifecycle of the fuel. Compared to gasoline's lifecycle GHG emissions of approximately 95 gCO_2eq/MJ, this estimate indicated that the reported benefits of ethanol were highly dependent on the feedstock. Shortly after *Science* published Searchinger's study, oil climbed to historically high prices, as did other commodities, including corn. This confluence of factors sparked the food versus fuel debate and has highlighted today's myriad of sustainability concerns – environmental, economic, and social – surrounding biofuels and other alternative transportation fuels.

Sustainability and the Alternative and Renewable Fuel and Vehicle Technology Program

From concerns regarding the issues identified above, including but not limited to preservation of California's land resources, food versus fuel arguments, and climate change, California expanded the scope of its attention to include the more general notion of sustainability. The questions raised by sustainability are far-reaching: What are the impacts of alternative transportation fuels on water resources or water quality? How will food prices be affected by increased biofuels? How will electricity providers meet the increased demand as a result of electric vehicles? What is the transition from conventional natural gas – a fossil fuel – to renewable biogas? These types of questions had no simple answers and reflected a lack of tools to help understand these issues.

The scope of this report is to develop an analytical framework to evaluate the sustainability of transportation fuels. This effort is part of a larger focus of the Energy Commission to refine and update the full fuel cycle analysis – or lifecycle analysis – of transportation fuels.

Sustainability is an interdisciplinary concept that considers competing environmental, economic, and societal goals, with the goal being the optimized integration of these three competing interests. The focus of this work, however, is limited exclusively to the environmental aspects of sustainability. More specifically, through conversations with Energy Commission staff, the scope of this work has been narrowed further to focus on water use, water quality, soil quality, and biodiversity. The selection of these impact areas for further research is not meant as a marginalization of other aspects of sustainability, but rather a reflection of the need to prioritize Energy Commission efforts based on limited time and resources. A key question posed by Energy Commission staff is: Which of these four sustainability parameters may be appropriate for inclusion in lifecycle models?

Currently, there is no debate on the sustainability of petroleum-derived fuels: Supplies are limited, the price of oil is volatile, and the environmental impacts are severe. The sustainability of new and alternative transportation fuels is not as straightforward. To face this challenge, as part of the development of the Alternative and Renewable Fuel and Vehicle Technology Program, the Energy Commission has been charged with the responsibility to "establish sustainability goals to ensure that alternative and renewable fuel and vehicle deployment projects, on a full fuel-cycle basis, will not adversely impact natural resources, especially state and federal lands."

The Energy Commission has since developed three sustainability goals, which can be summarized as:

- Reduce GHG emissions substantially.
- Protect the environment, including all natural resources, and promote superior environmental performance.
- Enhance market and public acceptance of sustainably produced alternative and renewable fuels using certified sustainable production practices and standards.

The Energy Commission has provided substance to these goals via eleven (11) evaluation criteria that were developed to assess how well proposed projects meet the sustainability goals. Apart from these goals and criteria, the Energy Commission has prepared a variety of position documents to clarify the operational definition of sustainability to inform stakeholders of how they plan to proceed. The Air Resources Board has responded similarly and recently formed a Sustainability Working Group as part of its development of the Low Carbon Fuel Standard. In a discussion paper the Energy Commission states the following (Energy Commission 2008):

> Intuitively, sustainability means "doing something better than it is done now, using resources more efficiently and less wastefully." It also compels us to think about the "unintended consequences" or unforeseen effects that can bedevil good government intentions. As a practical matter, for alternative fuels and vehicle technologies, sustainability must mean that these products are produced differently and in some sense "better" than conventional fuels.

In the same document, the Energy Commission goes on to discuss the role of sustainability and thresholds:

> The threshold issue ties closely to existing environmental regulatory standards. The presumed implication for a "sustainability threshold" is that it would need to be more stringent than existing legal standards and require environmental performance that exceeds standard business practices for entities seeking AB 118 program funding. This could mean that in a state such as California with fairly stringent environmental regulatory standards for air, water, toxics, land use, and biodiversity protection, a project that meets California's legally defined (through the permitting process) standards may not meet "sustainability standards."

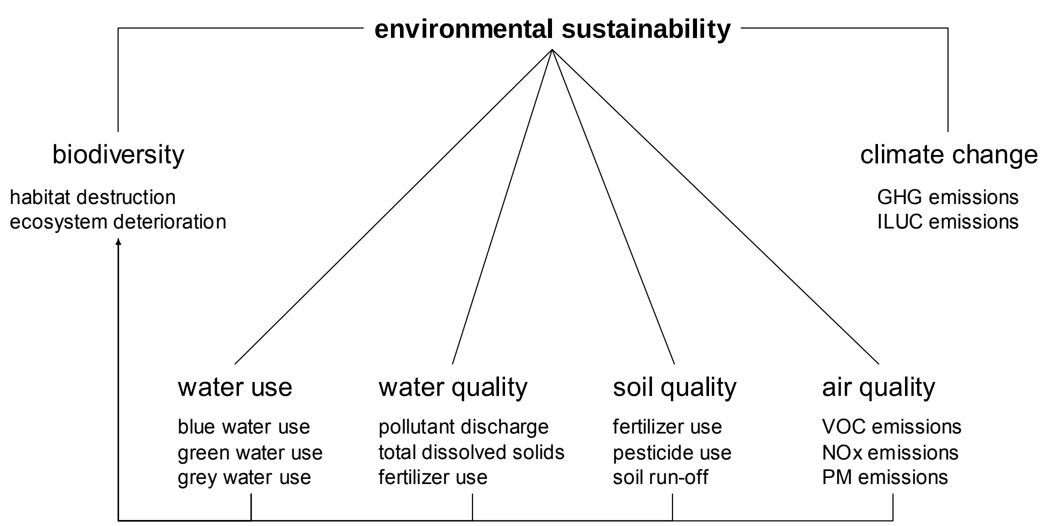
TIAX considers the presumed implication that more stringent sustainability thresholds are needed to be potentially misleading. The presumption implies that existing standards lead to unsustainable activity and processes. TIAX argues that dealing with environmental standards and issues in silos leads to unsustainable actions because tradeoffs and unintended consequences are poorly understood. Rather, sustainability thresholds should be part of a framework or platform to consider many (environmental) issues simultaneously, and not necessarily more stringently. The Energy Commission's development of sustainability goals, as discussed above, is more consistent with a multidisciplinary approach, with the second of three sustainability goals summarized as "protect the environment … and promote superior environmental performance" (Energy Commission 2009).

In the context of environmental issues, an issue or problem (e.g., air quality) is identified, and the policy or legislative response is generally directed at the causes of the problem. In the case of air quality, for instance, the problem arises from high ozone (O_3) concentrations or particulate matter (PM) concentrations. The policy response is to establish concentration thresholds. In the case of ozone, the authors use attainment and non-attainment, with various degrees of compliance within each category e.g., severe or moderate. The secondary policy response is to set standards on the pollutants that cause the air quality problem i.e., volatile organic compounds (VOC) and oxides of nitrogen (NO_x). The standards and regulations for VOC and NO_x emissions are the levers that policy makers use to reduce ozone concentrations. A similar policy response has developed in the response to climate change caused by GHG emissions.

In the case of air quality, the regulation of VOC and NO_x, among other pollutants has been an effective mechanism to improve air quality, which has drastically improved human health. In general, environmental problems are addressed in silos. As a result, in some instances, the effort(s) to solve one problem have created another. For instance, the replacement of lead in gasoline with MTBE is an excellent example. The same concerns about the toxicity of lead ultimately led to the ban of MTBE[3] when it was discovered in elevated concentrations in drinking and ground water. Presumably, in a sustainability framework, the issues surrounding the use of MTBE would have been considered across multiple media and areas of impact.

The challenge of developing a platform to consider environmental sustainability across multiple areas is the analytical determination of harm, in other words, the derivation of causes that lead to unsustainable effects. In the context of this report, the authors consider several environmental issues: water use, water quality, soil quality, and biodiversity. Other issues that are incorporated into AB 118 regulatory language includes air quality and climate change. Figure 1 shows how these issues are related and interrelated. For instance, the pursuit of environmental sustainability requires one to manage water resources; improve water, soil and air quality; mitigate climate change; and preserve biodiversity. To promote superior environmental performance, however, the issues that negatively or positively impact each of these areas must be understood. These issues are subsequently incorporated into an analytical framework using robust metrics. It is also worth reiterating that the research team's focus is limited to environmental sustainability i.e., the authors do not consider the social or economic aspects of sustainability.

Figure 1: TIAX Conceptualization of Environmental Sustainability



Source: TIAX LLC

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3 The authors are not equating the toxicity of lead and MTBE; they are only pointing out that concern about the toxicity of lead resulted in a ban and subsequent concerns about the toxicity of MTBE led to its ban.

There is a considerable amount of literature that explores the definition(s) and scope of sustainability, and how it can be measured by various criteria, metrics, and indicators. The authors have no intentions of (re)defining sustainability in this work. Rather, TIAX has adopted the same assumptions developed by the Energy Commission in regards to sustainability, namely that sustainability:

- Indicates lower impact, not necessarily zero impact.
- Encompasses global environmental and social issues and is not limited to California's resources.
- Requires environmental performance and production practices that exceed extant regulatory standards.
- Includes the entire lifecycle of transportation fuels.

Apart from the development of an analytical framework, the Energy Commission is also interested in ensuring that sustainability research conducted as part of the development of the Alternative and Renewable Fuel and Vehicle Technology Program is consistent with research efforts at federal agencies, international and national working groups, and other agencies. After TIAX and Energy Commission staff narrowed the scope of work for this project to water resources, water quality, soil quality, and biodiversity, TIAX spoke with individuals at various agencies – domestically and internationally – to ensure that the research was generally consistent with other ongoing efforts. TIAX contacted individuals at the following agencies: EPA, Department of Energy, Lawrence Livermore National Laboratory, Argonne National Laboratory, United States Department of Agriculture, National Renewable Energy Laboratory, Oakridge National Laboratory, the European Commission, Inter-American Development Bank, California Department of Fish and Game, and California Department of Water Resources. TIAX received positive feedback regarding the scope of work developed by Energy Commission staff and TIAX, with most individuals confirming similar or complementary interests at their respective agencies.

Overview of Report

This report is based primarily on a literature search of analytical research from peer-reviewed sources (e.g., academic journal articles) as well as the "grey literature" – which is characterized as government and/or consultant reports that are not necessarily academically or commercially published. Note that the focus is on analytical research, not simply quantitative assessments of sustainability or sustainability indicators. Due to the interdisciplinary study of sustainability, there may be a tendency or urge to aggregate various analytical metrics into a single measure of sustainability. This requires a subjective selection of weighting factors, as there is little to no analytical basis for valuing one element of sustainability over another. These weighting factors are primarily a function of stated goals rather than objective factors. As such, TIAX has purposely avoided making recommendations related to weighting factors and has instead focused solely on an analytical approach that will enable the Energy Commission to evaluate the sustainability of transportation fuels.

Chapter 2 outlines the research team's approach to the development of the analytical framework, and the objective of incorporating all transportation fuels into the framework. The authors emphasize the objective of differentiating between fuel production pathways based on environmental sustainability, but ultimately there are other considerations to answer the question of: is a fuel sustainable? The authors also discuss the criteria that TIAX developed to guide the literature search and the process for incorporating a particular impact into an analytical framework. Much of the research related to sustainability focuses on qualitative factors, or even on quantitative assessments that incorporate weighting factors. It is important, however, to distinguish between qualitative or quantitative research and analytical research. The criteria outlined help differentiate between these and provide focus for analytical aspects, rather than simply quantitative impacts.

In **Chapter 3** the authors discuss the areas of impact based on the literature review and consider the appropriate steps to incorporate metrics into a sustainability framework. The authors have also included a brief overview of how GHG emissions are accounted for in an analytical framework to assess the global warming impacts of transportation fuels. The authors discuss both the tool (the GREET model) and the metric (grams of CO_2 equivalent per unit energy of fuel, g CO_2-eq/MJ). This is a useful example, as it highlights the analytical rigor and consensus that are required to develop an analytical framework. After the review of GHG emissions of transportation fuels in the context of the GREET model, the authors review the potential impacts of transportation fuels on water resources, water quality, soil quality, and biodiversity.

In **Chapter 4** the authors make conclusions and recommendations to bridge gaps between existing knowledge and the development of an analytical framework to evaluate the sustainability of transportation fuels. These recommendations identify the areas of research that can bridge or strengthen the bridge between the field of interest and the development of an analytical framework to evaluate the sustainability of transportation fuels.

CHAPTER 2:
Approach to Framework Development

In this report, in coordination with the Energy Commission and through conversations with various experts at local, state, and national research agencies, the research team identified the following areas of impact for further consideration as part of an analytical framework to assess the sustainability of transportation fuels:

- Water resources
- Water quality
- Soil quality
- Biodiversity

Analytical Versus Quantitative

The challenge of developing an analytical framework for sustainability considerations of transportation fuels is that there is not much precedent in this area. To date, sustainability has largely been assessed on a *qualitative* basis rather than an *analytical* basis. This is an important distinction because it frames the problem in a decidedly different fashion. The analytical aspect of sustainability suggests an emphasis on basic principles. In other words, the discussion of sustainability as a holistic approach that reflects environmental, economic, and social concerns has limited utility in the development of an analytical approach. The research team's approach must separate and break down the sustainability impacts into their constituent parts and variables. For instance, in each of the areas of impact – water use, water quality, soil quality, and biodiversity – the authors have a qualitative understanding of what is "good": Don't use too much water, don't pollute water ways, don't pollute the soil, and maintain or improve biodiversity. The approach here is to break down those qualitative and, in some cases, quantitative measures into variables and parameters that can be measured to differentiate between the bad, the good, and the better of the unsustainable and sustainable.

A number of organizations have developed criteria to assess the sustainability of fuels, primarily focused on biofuels (Groom, Gray et al. 2008; CSBP 2009; RSB 2009; Stahlbush 2010). Similarly, the Roundtable on Sustainable Biofuels (RSB) has developed 12 principles and 37 sustainability criteria (RSB 2009). The criteria can generally be described as guidance to stakeholders e.g., biofuel providers and policy makers, rather than scoring criteria to identify the most sustainable approaches.

In another example, the Inter-American Development Bank (IDB) has developed a sustainability scorecard to "provide a tool to think through the complex issues associated with biofuels from the field to the tank." The scorecard is designed to assess both environmental and social elements of sustainability; however, the IDB explicitly claims that the scorecard should not be used to replace certification schemes or lifecycle assessment tools (IDB 2009). On the environmental side, the scorecard lists 5 primary areas of interest, with 18 secondary areas. The scoring method is qualitative and is based on what is essentially a 5-point scale represented by colors, ranging from bright green (excellent) to red (unsatisfactory).

It is important to note that neither the RSB nor the IDB has a goal of developing an analytical framework to assess the sustainability of transportation fuels. The research team's objective is considerably different than theirs and requires a different approach.

It is worth noting that the research team's scope is limited to research and recommendations of metrics for an analytical framework, and not the aggregation of metrics across each area of impact. Furthermore, the authors' research is focused on environmental sustainability factors. In other words, the authors' research is intended to provide guidance for analyzing the environmental sustainability of transportation fuels, rather than an answer to the question: Which fuel pathway is sustainable?

Establish a Consistent Approach

As discussed, there is concern regarding expanded use of biofuels due to indirect land use change, competition with the food supply, and other factors. The goal of the discussion was to highlight one of the motivating factors behind incorporating sustainability language into AB 118, not to demonize the biofuel industry. In fact, any given fuel could be scrutinized in a similar fashion – the biofuel discussion is simply the most recent debate. It is fair to assume that as electric vehicles, a popular technology option in the transportation sector right now, become more popular, electricity as a transportation fuel will come under increasing scrutiny: Is the transmission and distribution infrastructure sufficient? How is the electricity being generated? How secure is the supply of lithium? And how environmentally sustainable is lithium mining? These questions will undoubtedly be raised over time.

One of the objectives of this work is to help differentiate among fuel options over a number of considerations simultaneously, rather than one issue at a time. In other words, the metrics that are employed in the analytical framework should be applicable across fuels and establish a consistent approach. The fuels to which the framework should apply include gasoline and diesel, biofuels (e.g., ethanol or biodiesel), natural gas (compressed and liquefied), electricity, and hydrogen. Fuel production pathways will have varying degrees of impact in the areas of interest – water use, water quality, soil quality, and biodiversity – but, in principle, the metrics employed should be applicable across the board.

At first glance, it is clear that biofuels will have a more significant impact on soil quality than electricity, for instance. The objectives, however, are to determine what the impact will or might be for each fuel pathway and determine how significant the differences are. Furthermore, is the impact of electricity generation on soil quality zero? The analytical framework is a means to take this discussion from the hypothetical to the practical.

Analytical Criteria to Filter Recommendations

As part of the literature review, TIAX developed analytical criteria to guide this research. The objective of these criteria is to ensure that the metrics and variables considered within each area of impact – water resources, water quality, soil quality, and biodiversity – are valid and appropriate for consideration in an analytical framework to assess the sustainability of transportation fuels. The challenge of this task is derived from the need to develop an *analytical* framework.

TIAX developed the following criteria to consider during the literature review of existing metrics to evaluate the sustainability of transportation fuels. Each criterion relates primarily to the area of impact under consideration but also considers the variables, parameters, and metrics that are used to quantify the impacts in each area of concern.

1. The impact(s) must be measurable, quantifiable, and verifiable.

In each area, the research team must consider whether the impacts are developed using data that can be measured in the field. If data cannot be measured, then models can be employed; however, the data that are generated from modeling must be explicitly identified as such.

Apart from being measured, the impacts must be quantifiable. In other words, a qualitative impact is insufficient to include as part of the analytical framework.

Finally, the impacts must be verifiable. The verification of impacts includes a confluence of factors such as peer-reviewed data, public accessibility, transparency, and clearly identified boundary conditions. The verification requirement is a quality assurance and quality control mechanism.

2. There should be a reasonable degree of consensus regarding the approach to quantify the impact(s) in question, and there should be agreement regarding the utility of the related metrics.

The authors seek an approach that has a reasonable level of consensus amongst experts in the appropriate field. The framework proposed has a number of cross-cutting themes. As such, it is important that the approach to quantify the impact(s) is consistent with the level of knowledge in the corresponding field.

In addition to consensus in the various fields of research regarding the approach, the authors hope to identify variables and metrics that have maximum utility in the assessment of sustainability impacts.

CHAPTER 3:
Review of Findings for Each Area of Impact

In the following sections, the authors review each area of sustainability over a number of steps. In each section, the research team will:

- **Review each area of impact** and provide a basic overview of the area considering its importance in the context of sustainability. The authors provide the definition of what is considered in this report and where appropriate, they discuss how and why the definition is similar to or different than what is used elsewhere.
- **Assess the current state of knowledge** based on the literature review.
- **Identify the metrics used for each area of impact** where appropriate. These metrics are evaluated in the context of the review criteria that the authors have outlined in Chapter 2.
- **Suggest how the data could be incorporated into an analytical framework** to assess the sustainability of transportation fuels. This section includes the following:
    - **Discuss appropriate comparative basis.** The purpose of this section is to discuss ways to develop a methodology that avoids cross-talk of marginal and average considerations and to ensure that the comparison is done on an equivalent basis i.e., apples to apples. For instance, the research team will explore the challenge of assessing each fuel on an average or marginal basis.
    - **Discuss boundary conditions.** To date, the focus of lifecycle impacts of transportation fuels has focused on GHG emissions, which are considered uniform across space. The local and regional conditions that affect water use, water quality, soil quality, and biodiversity make it more challenging to incorporate these issues into an analytical framework. For example, it will be difficult to develop fuel pathways that are broadly representative in the same way that fuel pathways were developed for GREET modeling. Boundary discussions are discussed in the context of geographical considerations, direct vs. indirect considerations, and selecting pathways based on minimum market potential (as determined by technical and economic feasibility).
    - **Identify data to compile for reference cases.** The development of an analytical tool to evaluate the sustainability of transportation fuels will require the development of reference cases. In this section the authors identify the types of data and variables that will need to be inventoried to develop appropriate reference cases. The objective of this discussion is to narrow the field of potential reference cases by highlighting the most relevant variables and parameters in each area of impact, thereby minimizing the uncertainty of each reference case.
    - **Discuss weighting factors.** Weighting factors are generally subjective and are reflective of value judgments based on policy goals. Many of the areas of impact that TIAX investigated will require a composite of indices or the simultaneous consideration of several variables. It is beyond the research team's scope to

quantify weighting factors as part of our analysis. The authors will, however, identify the key variables and discuss their relationships. The authors also identify what they consider as potential pitfalls associated with some variables, as appropriate.

Before the research team's review of each sustainability consideration, the authors have provided an overview of how the GHG emissions of transportation fuels are accounted for on a lifecycle basis in an analytical framework. This provides a useful example that the authors seek to replicate – with appropriate and relevant changes – for the other areas of sustainability under consideration.

Greenhouse Gas Emissions

GHG emissions are the primary driver for global climate change resulting from the greenhouse effect, which leads to, among other problems, unsustainable increases in the global mean temperature. The most common GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases e.g., sulfur hexafluoride and HFCs. The impact of a particular GHG is measured by its global warming potential (GWP), reported over various time scales e.g., 20 or 100 years. The GWP of CO_2, for instance, is 1 over all periods. Methane and nitrous oxide, however, are about 25 and 300, respectively, over a 100-year time horizon.

GHGs are considered to be well-mixed in the atmosphere, which means that the problem is global in nature. Therefore, the global warming impact is independent of geographic distribution.

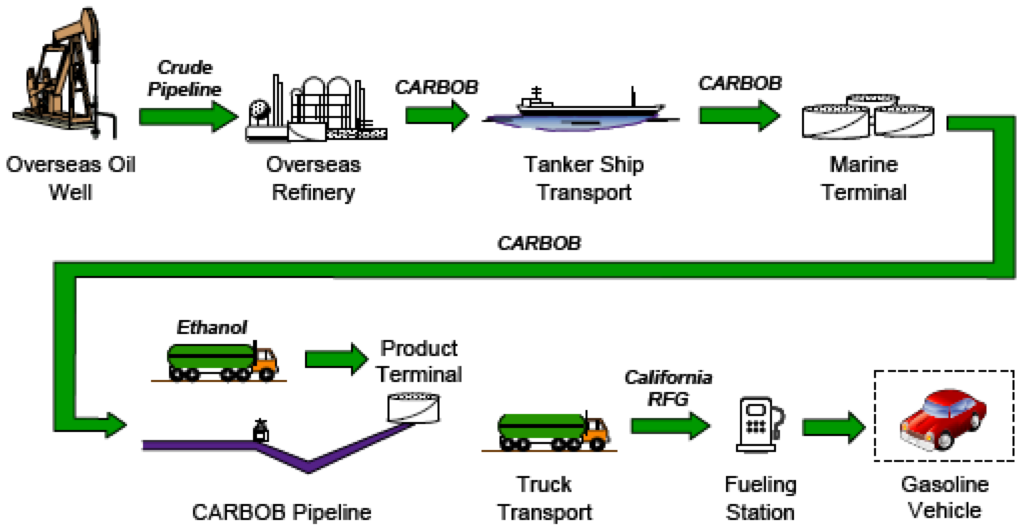
The most widely accepted tool to quantify the GHG emissions attributable to transportation fuel pathways is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. The GREET model was developed by Argonne National Laboratory and has been undergoing periodic revisions and updates since the release of the original version in 1996, the most recent occurring in March 2008. The development process has benefitted from input from the U.S. Environmental Protection Agency (EPA), Department of Agriculture, Department of Energy Laboratories, California agencies (e.g., the Energy Commission and Air Resources Board), and industry representatives. The GREET model provides well-to-wheel analysis and, as a result, assesses the impact of the full fuel cycle as well as the efficiency and emissions associated with the consumption of fuel in various vehicles. At present, the GREET model includes more than 100 fuel production pathways from various energy feedstocks. In assessing these various fuels and pathways, the GREET model attempts to quantify the emissions of greenhouse gases, criteria pollutants, and energy consumption. (See Table 1.)

Table 1: GREET Model Considerations

fuel impact	specific considerations	notes
GHG emissions	CO_2, CH_4, N_2O	as defined by the IPCC
criteria pollutants	VOC, CO, NOx, SOx, PM10, PM2.5	spatial: urban vs. non-urban
energy sources	petroleum, coal, natural gas, non-fossil	

Source: TIAX LLC

Figure 2: Full Fuel Cycle of Imported CARBOB



The imported CARBOB to reformulated gasoline fuel pathway, including upstream emissions.
Source: TIAX LLC

The energy inputs along the fuel pathway (as shown, for instance, in Figure 2) are well understood for most transportation fuel pathways. The energy balance is measureable, quantifiable, and (generally) based on in-use data on an average basis. There are variations, for instance, in crudes, feedstocks, and refining processes. However, for each step of the fuel production pathway, there are multiple points of data available that can be used to develop an average picture of the energy required and therefore the GHG emissions associated with the production of transportation fuels. It is also worth noting that the boundary conditions for the problem are clearly laid out in the schematic, as shown in Figure 2.

The accessibility and flexibility of the GREET model have helped develop consensus and provided a platform for agreement among stakeholders – including academia, government/research agencies, and policy makers. The model is publicly available and built on a MS Excel® platform. This access allows for unrestrained review and comment from a variety of stakeholders, which is an integral part of GREET development. Over its lifetime, GREET has been reviewed by a variety of stakeholders, including General Motors, the National Corn Growers Association, several fuel industry organizations, and a wide variety of educational institutions. In addition to the availability for feedback, public access allows interested parties to change inputs, modify the assumptions and utilize the model for independent analysis. The GREET model was modified by TIAX in 2007 (CA-GREET) to capture and quantify the lifecycle GHG emissions of fuels entering the California market, most notably the unique mix of electricity generation resources and haul distances. The CA-GREET Version 1.8(b) is the model currently used by the Energy Commission and the Air Resources Board (for compliance with LCFS). The GREET model is also used by the EPA to assess the regulatory impact of the renewable fuel standard as part of the Energy Independence and Security Act (EISA) of 2007.

The lifecycle GHG emissions of fuel pathways are generally reported as grams of CO_2 equivalent emissions per megajoule of energy in the fuel (g CO_2-eq/MJ). This metric is a simple and elegant way to compare fuels based on the energy input required to produce the fuel at each stage of production, as compared to the energy content of the fuel. Other metrics, such as grams of CO_2 equivalent per mile can be useful; however, there are embedded assumptions regarding the fuel economy of a vehicle in that metric. The g/MJ metric emphasizes the impact of the fuel, rather than the fuel/vehicle combination.[4] Furthermore, the g/MJ metric simplifies the calculation of GHG emissions (or reductions) for fuel policy making.

The sustainability impacts considered below – water resources, water quality, soil quality, and biodiversity – require a different approach than GHG emissions. The boundary conditions are identical, in that the authors must account for the impact at each stage of fuel production, most notably at the farm level for biofuels. However, the impacts are not uniform across time (in the 50-100 year time scale, at least) and space, as is the case with GHG emissions. The local and regional conditions will have a much greater role in the integrated assessment of the sustainability of transportation fuels when moving beyond the energy balance accounting performed as part of GREET modeling.

Water Resources

Water resources and water use in the production of transportation fuels are of particular concern due to the water demand of bioenergy crops for biofuels. Although other alternative fuels e.g., electricity or hydrogen, can impact water availability, biofuels will have the greatest impact. If biofuels are to play an important role in the transportation sector, then policy makers must consider the implications of increased agricultural activity and subsequent fuel processing and production on water resources. The biofuels industry is already responding to the concerns raised; POET – an ethanol company – recently announced its Ingreenuity[5] initiative to “enhance the environmental performance of ethanol.” The first goal of the initiative is to reduce the amount of water it takes to produce a biofuel by 22 percent compared to today’s water usage rate.

There are a myriad of definitions and parameters that are used to understand water use. The most relevant definitions and distinctions are reviewed briefly here:

- **Evapotranspiration**: Water is lost to the atmosphere in the process of transpiration, in which water diffuses from inside leaves via the stomata. Water is also lost to the atmosphere via evaporation from the soil and plant leaves. Collectively, these losses are evapotranspiration losses.
- **Consumption Versus Withdrawal**: In King and Webber (2008) water consumption includes water that is taken from surface water or groundwater sources and not directly returned, and water withdrawal includes water that is taken from surface water or groundwater, used in a process, and returned to its original source. Similarly, in Berndes

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4 There are other standards in place to improve the efficiency of vehicles and reduce fuel consumption thereby reducing GHG emissions. The Pavley standards (AB 1493) and the new CAFE standards for MY 2012-2016 vehicles are targeted to reduce GHG emissions from vehicles in California and improve fuel economy at the federal level, respectively.

5 http://www.poet.com/sustainability/ingreenuity_water.asp

(2002) water use that requires water is withdrawn from its original location is termed withdrawal. The part of withdrawn water that evaporates due to its withdrawal is referred to as consumed water. Although there is no explicit mention in Berndes (2002) of whether the water is returned to its source to distinguish between consumption and withdrawal, in principle the two definitions are equivalent.

- **Green Water Versus Blue Water:** Green water refers to precipitation i.e., rain and blue water refers to water that is withdrawn for irrigation from rivers, lakes, and aquifers. Although the most important impacts on water availability are due to blue water for irrigation, recent studies have shown that changes in green water can have implications for water resources at a landscape level (Starr, Clark et al. 2005; Berndes 2008; Trabucco, Zomer et al. 2008.)

It is worth noting that the concerns addressed in this section pertain exclusively to fresh water i.e., the impacts on salt water have not been included. The authors recognize, for instance, that in California there are concerns related to saltwater and shorelines, specifically due to offshore oil production and the transport and refining of oil products. Salt water resources include ocean waters, shorelines, tidelands, and sloughs. The commercial interests related to these resources include, but are not limited to, harvesting ocean fish, kelp, and shellfish, saltwater fish farming, wildlife interests, and sizeable portions of California's tourist and recreation industries. With this delimitation of saltwater from the research team's scope of work, the remainder of the authors' analysis focuses on the types of resources most frequently addressed in the scientific literature pertaining to the sustainability of transportation fuels.

Current State of Knowledge

There are many studies that have assessed the impacts on water availability due to increased use of biofuels. A sample of them is reviewed here. The studies vary in several respects, most notably:

- **Scale**: global, national, regional, state
- **Crops/fuels considered**: Studies evaluated crops ranging from traditional bioenergy crops such as corn and sugarcane to next generation bioenergy crops such as miscanthus or sweet sorghum. A handful of studies also included the water use requirements for other transportation fuels.
- **Temporal variations**: Most studies were based on current agricultural and production processes. Some studies projected water requirements based on meeting a defined goal e.g., targets established by the Energy Independence and Security Act of 2007.
- **Metrics**: Studies reported the amount of water required to produce a particular (bio)fuel in a variety of ways. These are discussed in more detail below.

A key question from Energy Commission staff is: Which of these typologies best account for regional variance in hydrologic cycles? Furthermore, is it possible to make rational, objective comparisons between regions such as Malaysia (100 – 150 inches annual precipitation), Iowa (26 – 38 inches), and California's Imperial Valley (< 3 inches)?

Berndes (2002) focused on global scale bioenergy production to estimate the increase of evapotranspiration (ET) globally, as compared to current ET levels from agriculture. He focused on crops such as rapeseed, sugarcane, sugar beet, corn, and wheat, as well as lignocellulosic crops such as miscanthus. They provided ranges of water use efficiency (WUE) for these crops and the amount of water per unit of gross bioenergy.[6] The analysis was meant only to provide a birds-eye view of the expanding bioenergy sector and indicated that the ET increases from bioenergy crops will be large and will impact countries differently.

Gerbens-Leenes et al. (2009) focused on the water footprint (WF) of 13 crops, reported as cubic meters of water per gigajoule of gross bioenergy (m^3/GJ). Furthermore, they distinguished between green WF and blue WF. They provided low, high, and weighted-average global values for the WF of 10 crops used to produce ethanol and 3 crops to produce biodiesel. The authors noted large variations for similar crop types due to agricultural production systems and climate conditions. Notably, their study also investigated the water-energy intensity of biomass crops to generate electricity; they concluded that it is more water-efficient to use total biomass – including stems and leaves – to generate electricity than to produce a biofuel. This is particularly interesting because in another recent study, Campbell et al. (2009) concluded that bioelectricity would produce more GHG emission offsets (i.e, reductions) than biofuels based on energy and land use efficiency.

In a separate study, de Fraiture et al. (2008) estimated the land and water requirements that would be needed to fulfill the forecasts of the International Energy Agency where biofuels are actively promoted by government support. They forecast 5.3% global annual growth in biofuels (in billion liters/year) to 2030, which would account for 7.5% on an energy equivalent basis of transportation fuels. A globally averaged analysis showed that this growth would require about 30 million additional hectares (ha) of cropland with a corresponding irrigation withdrawal of 180 km^3. This compared with food crop requirements of about 1,400 million ha and irrigation withdrawal of about 3,000 km^3. The authors noted that individual crops may increase substantially, but compared to the sum of all crops, the increases are modest. More specifically, these increases amounted to an increase of 2-5%, which they concluded are "too small to lead to major changes in agricultural systems at a global level." The authors issued a note of caution, however, and showed that in countries like China and India, where there is already regional and seasonal water shortages, these seemingly small increases are unsustainable due to over-exploitation. These country-specific variances highlight the concerns at the local and regional level regarding water use.

A number of researchers have quantified the water use of biofuels in the United States. For instance, Wu et al. (2009) evaluated the water consumption in the production of ethanol from corn and switchgrass from USDA farm Regions 5, 6, and 7. (See Figure 3.) They report freshwater consumption via irrigation and processing water requirement, with a range of 10–324 liters of water per liter of corn ethanol and 1.9–9.8 liters of water per liter of switchgrass ethanol. In the same study, the authors also investigated the consumptive water requirements of U.S. conventional crude from PADD II, III, and V, Saudi conventional crude, and Canadian oil sands via various extraction techniques, including cyclic steam stimulation (CSS), steam

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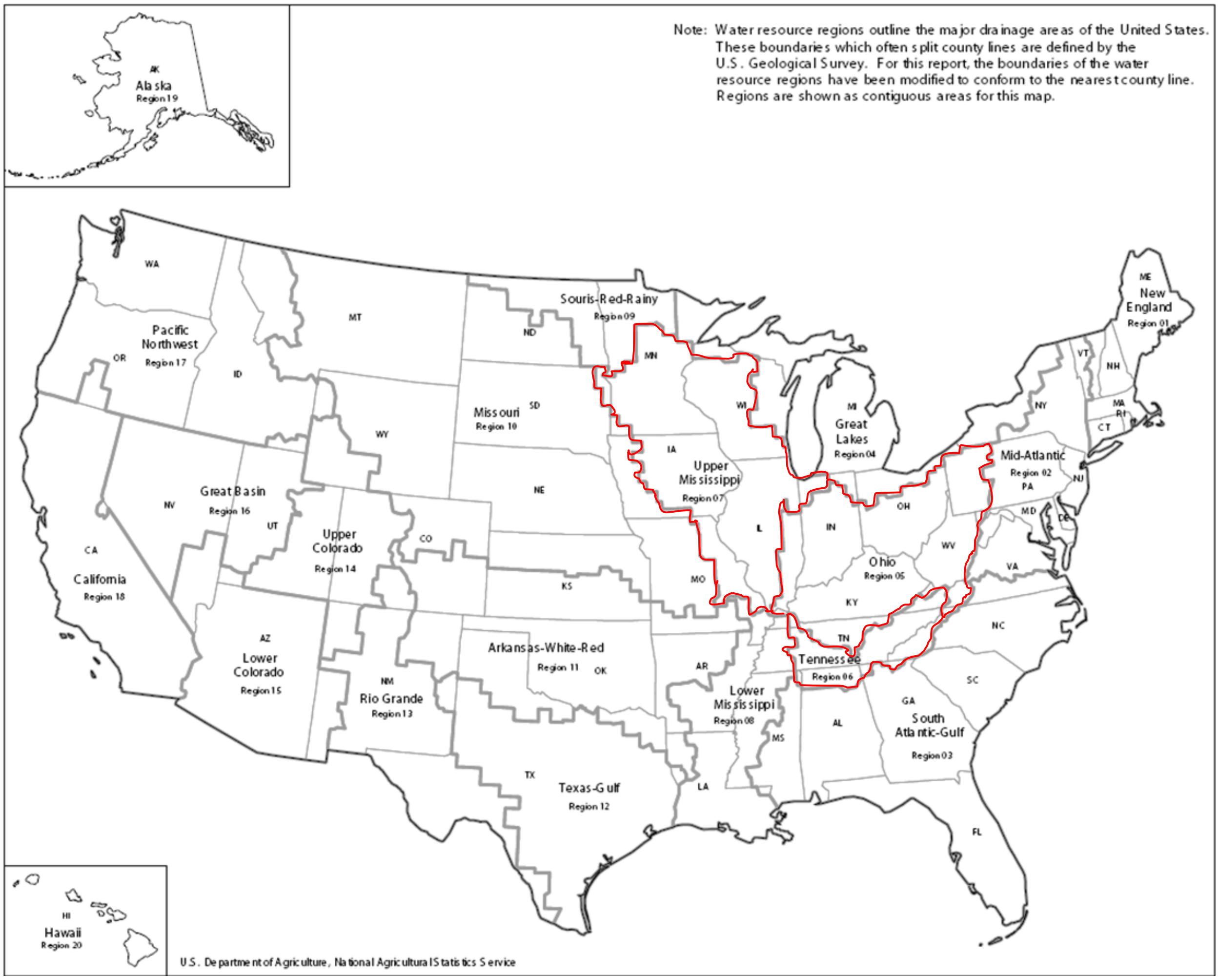
6 Note that *gross* bioenergy includes only the energy of the biomass and is not to be confused with *net* bioenergy, which would also account for the energy inputs in the production chain.

assisted gravity drainage (SAGD), surface mining, and a multischeme approach that combined various aspects of CSS, SAGD, and other recovery techniques (Table 2).

Figure 3. Water Resources Area Map of the United States



Note that Regions 5 (Ohio), 6 (Tennessee), and 7 (Upper Mississippi) are highlighted in red.
Source: (USDA 2004)

Table 2: Water Consumption for Ethanol and Petroleum Gasoline Production

ethanol		irrigation	production	total
ethanol, corn	Region 5	7.1	3.0	10.1
	Region 6	13.8	3.0	16.8
	Region 7	320.7	3.0	323.7
ethanol, switchgrass	fast pyrolysis	--	2.2	2.2
	gasification	--	1.9	1.9
	biochemical, future	--	5.9	5.9
	biochemical, current	--	9.8	9.8

gasoline		E&P [a]	refining [b]	total
gasoline, US crude	PADD II	1.9	1.5	3.5
	PADD III	2.2	1.5	3.7
	PADD V	5.1	1.5	6.7
gasoline, Saudi crude	North ‘Ain Dar	4.3	1.5	5.8
	Ghawar	1.3	1.5	2.8
gasoline, Canadian oil sands	multi-scheme	4.7	1.5	6.2
	CSS	2.0	1.5	3.6
	SAGD	1.2	1.5	2.7
	surface mining	3.7	1.5	5.3

[a] E&P – extraction and production

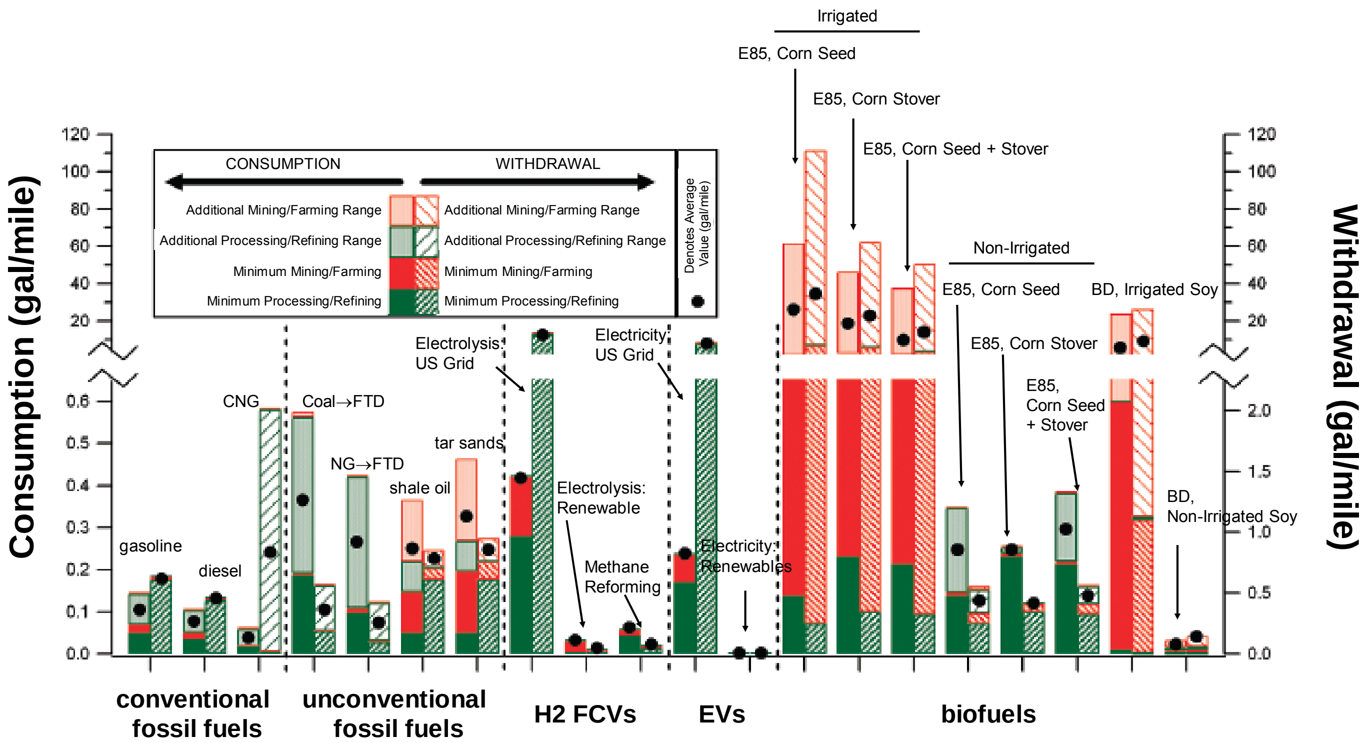
[b] Wu et al. assume a constant value of 1.53 L/L for oil refining of conventional crude and for synthetic crudes.

Values are shown in liters of water per liter of fuel.

Source: Adopted from tables, graphs, and data in Wu et al. (2009)

King and Webber (2008) evaluated the water usage for automotive fuels on a lifecycle basis. They reported their results, distinguished as consumption and withdrawal, for conventional fossil fuels, unconventional fossil fuels, hydrogen fuel cell vehicles (FCVs), electric and plug-in hybrid vehicles, and biofuels (Figure 4). Their report was unique in that they considered the impact of many of the pathways of transportation fuels on water resources, rather than exclusively focusing on biofuels, as in other studies.

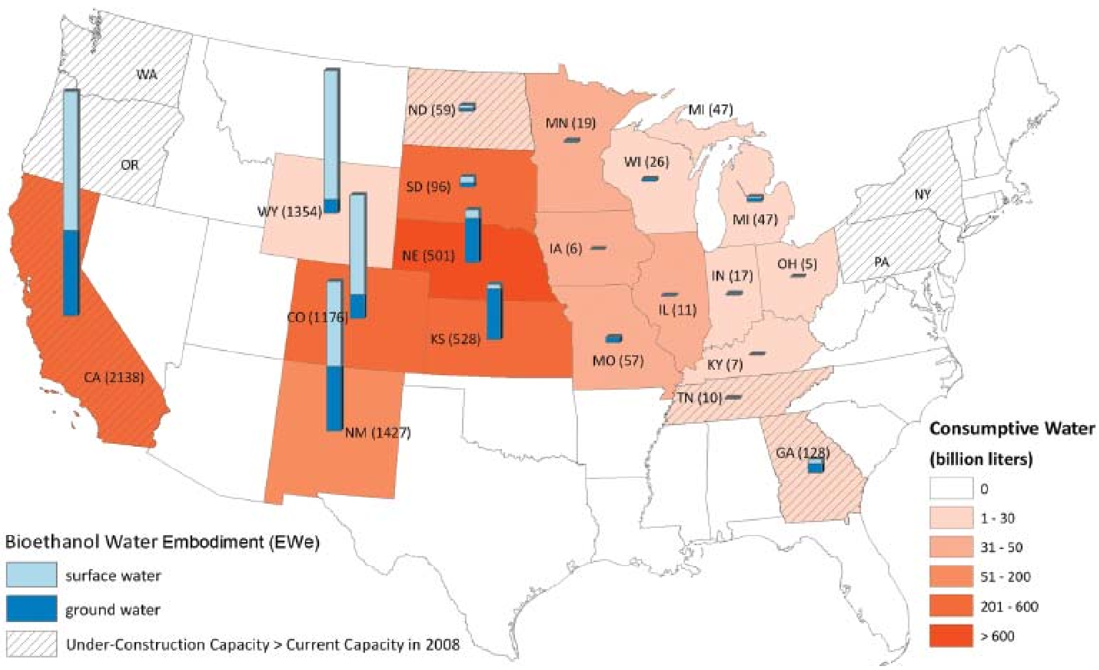
Figure 4. Water Consumption and Water Withdrawal of Transportation Fuels



Water consumption and water withdrawal (in gallons of water per mile driven) are reported on the left and right axes, respectively, for transportation fuels. CNG – compressed natural gas, FTD – Fischer Tropsch Diesel, E85 – 85 percent ethanol blended with 15 percent gasoline, BD – biodiesel, H2 FCV – hydrogen fuel cell vehicle, and EV – electric vehicle (including battery electric and plug-in hybrid electric vehicles).
Source: King and Weber (2008).

Chiu et al. (2009) further demonstrated the variation in water consumption in corn ethanol production by examining water use and production in each of the 41 corn-producing states. They reported a range of 5–2138 liters of water per liters of ethanol produced in Ohio and California,[7] respectively. (See Figure 5.) They considered only water from irrigation and process water from biorefineries and neglected any direct precipitation. This is a much wider range, and much clearer picture of the variable water use in ethanol production than the 263–784 liters of water per liter of ethanol reported as a national average elsewhere (Pimentel 2003; Pimentel and Patzek 2005; Fraiture, Giordano et al. 2008; NRC 2008). The range and work done by Chiu et al. highlight an important aspect of water use in the production of transportation fuels: The water use depends significantly on the location of the crop. The authors further claim that "nationally averaged irrigated water figures are irrelevant in understanding ethanol's water implications, and the discussion should account for regional variations on a local basis."

Figure 5: Water Requirements for Corn Farming in the United States



The corn farm to fuel pump water requirement per liter of ethanol, reported as embodied water in ethanol (EWe, the blue bars) and the total consumptive water use (TCW, the shade of red) use, reported as the sum of process water at biorefineries (W_P) and irrigated water (W_{IR}).

Source: Chiu et al. (2009).

Evans and Cohen (2009) took a closer look at the southeastern United States to examine bioethanol production that would be required to meet the renewable fuel targets in EISA. They investigated both the blue and green water resource requirements for bioethanol derived from corn, sugarcane, sweet sorghum, and pine in Florida and Georgia to meet the renewable fuel targets by 2020. Their work led them to conclude that the associated water resource implications

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7 Note that California produces about 26 million bushels of corn annually – none of which is currently used for ethanol production – compared to about 2.4 billion bushels of corn annually in Iowa.

of biomass-to-ethanol processes suggested the need for an explicit consideration of environmental trade-offs with increased feedstock production is needed. Furthermore, if the Southeast is to meet its fair share of the renewable fuel target in EISA (i.e., about 10% of the 36 billion liters of ethanol), existing pressures on water (and land) resources will likely be exacerbated.

Preliminary research from Fingerman et al. (2010) evaluated the hypothetical embedded water content of biofuels grown in different counties in California using corn, sugar beets, low-yield biomass, and high-yield biomass. The authors developed three biofuel production pathways, developed in response to the LCFS in California, using:

- Conventional feedstocks – corn and sugar beets.
- Cellulosic crop feedstocks – corn, sugar beets, low- and high-yield biomass crops.
- Waste utilization – low- and high-yield biomass crops, agriculture/forestry residues, and industrial/municipal wastes.

The authors also characterized four displacement pathways to account for the change in resource allocation:

- Average field crops are displaced
- The thirstiest crops are displaced
- The least thirsty crops are displaced
- Extensification of agriculture occurs solely on uncultivated land

Each of the three biofuel production pathways is coupled with each of the four displacement pathways to develop 12 scenarios. Based on these scenarios, the authors predicted the impact on water resources across California. They report a weighted average for the embedded water content of ethanol at about 900–1500 liters of water consumed per liter of ethanol produced, depending on the feedstock.

Metrics

The metrics employed for understanding the impact on water resources of transportation fuels generally account for the quantity of water consumed to generate a liter (or gallon) of fuel. Due to the policy focus on biofuels, most literature within the last several years has also focused on the water demands of producing biofuels; however, the number of studies that consider water resources in a more general sense is increasing (King and Webber 2008; Wu, Mintz et al. 2009). King and Webber (2008) report the impact on water resources as gallons of water consumed per mile. In other words, the fuel economy of the vehicle is incorporated into their data. From a policy perspective, the presentation is convenient; however, by embedding the fuel economy of the vehicle into the metric, it is challenging to compare the fuels.

In the most comprehensive lifecycle analysis study that TIAX found, Pfister et al. (2009) assessed the environmental impacts of freshwater consumption, with a case study on the cotton textile industry. (See Table 3.) The authors included factors beyond water content, such as water stress index (WSI), which considers withdrawal compared to hydrological availability, health damages due to water scarcity (e.g., water shortage for irrigation, resulting in malnutrition), ecosystem damages as a function of potentially disappeared fraction (PDF) of species, and resource damages as measured by the back-up technology to assess abiotic resource depletion (Goedkoop and Spriensma 2001). Much of the modeling was done at the national level, depending on data availability. The authors focused on developing countries for human health damages, as these were the places where water scarcity was most likely to lead to local competition for water resources and thereby leading to malnutrition. For ecosystem damages, the authors used net primary production (NPP) as a proxy for ecosystem quality, based on correlation between NPP and vascular plant species biodiversity (VPBD).

Table 3: Inventory Data and Environmental Impacts Per Kg Cotton Textile

	global production share	consumptive use (m^3/kg)	water deprivation (m^3/kg)	ecosystem quality (PDF m^2 yr/kg)	human health (10^{-6} DALY/kg) [a]	resources (MJ/kg)	% of total damage causes by water consumption [b]
China	27.2%	2.35	0.93	0.449	0.61	3.97	5%
India	19.9%	5.73	5.16	2.12	11.93	15.0	24%
United States	16.4%	1.90	0.75	0.465	0.003	2.80	4%
Pakistan	8.5%	9.88	9.17	15.7	20.68	41.6	52%
Brazil	5.6%	0.61	0.01	0.0188	0.004	0.00946	0%

[a] DALY is disability adjusted life years
[b] fraction of total damage caused by water consumption based on LCA results using Eco-indicator-99 model

Results from the analysis performed by Pfister et al. (2009) to understand the irrigation requirements, yields, and environmental impacts from water consumption from the cotton textile industry. Only the top five producing countries are shown, accounting for nearly 78% of global production.
Source: Pfister et al. (2009)

Framework Development

The research reviewed above highlights the need for a detailed understanding of the local and regional watershed to perform a valuable assessment of the water resource impacts of transportation fuels. With respect to bioenergy crops, the local climate, soil conditions, crop type, and water availability play a significant role in determining the impact on water resources. There are generalizations that can be made with respect to the literature reviewed here, most notably that biofuels will add to water stress in many areas. The magnitude of this stress, however, is not well understood in all areas due to lack of research and data availability.

Regardless, research suggests that due to the local and regional nature of the problem, it will be difficult or impractical to distill the impact on water resources into a single metric. Fingerman et al. (2008), for instance, have suggested that a "price" for water be determined in global warming units and added to the average fuel carbon intensity. This type of quantitative manipulation will inevitably marginalize some of the local and regional concerns associated with water availability and may increase the chances of making an unsustainable decision. There is no analytical basis for normalizing the impacts of transportation fuels on water resources and global climate change that would yield an additive relationship with fuel carbon intensity. An economist may argue that researchers could estimate the damage costs associated with water resources and global climate change, and that these damages would be additive. However, the amount of information required to price both of these variables within a reasonable amount of uncertainty is unlikely to be available.

The approach outlined by Pfister et al. (2009) is new and has not received the appropriate scrutiny, but warrants further consideration and investigation as part of the analytical framework. Their research highlighted the difficulty of assessing the sustainability impacts of transportation fuels: lack of available data at local and regional levels and the complexity of estimating the impacts of water consumption on a lifecycle basis. The authors reported impacts over many dimensions: consumptive water use, water deprivation, ecosystem quality, human health, and resources. The authors reported a national-level impact of the cotton textile industry over these dimensions, with a single number indicated as "fraction of total damage caused by water consumption." Although the authors have opted to report the damages in this single number, it is possible that multiple metrics can be employed – including the ones outlined in their report – rather than relying on a cumulative "silver bullet" metric.

Comparative Basis

All transportation fuels will have some corresponding water withdrawals. Fuel pathways should be compared based on two criteria: 1) how much water is used (as distinguished by green, blue, or grey water) in the fuel pathway and 2) what is the water stress index of the area where water is being used. The former is straightforward and simply requires rigorous detailed accounting and verification of various fuel production processes. There is already considerable research in this area.

The second criterion is the more challenging aspect of water resource depletion, as the Energy Commission will need to determine stress index thresholds. Fortunately, however, there is already considerable research in this area, and the Energy Commission can draw from the thresholds defined elsewhere. For instance, as reported in Pfister et al (2009), moderate and severe water stress occur above a threshold of 20% and 40%, respectively. However, these thresholds are based on expert judgments and can vary. For instance, severe water stress may be reported with a ratio of anywhere between 20% and 60%. The Energy Commission should coordinate with subject experts to determine the appropriate thresholds consistent with the sustainability goals of the Alternative and Renewable Fuel and Vehicle Technology Program. This, for instance, may require consideration of existing water stress indices for fuel pathways listed in the LCFS.

Boundary Conditions

The issue of boundary conditions comes into play for water resource use in the determination of water stress indices. In other words, how large is the area that should be considered as impacted by the withdrawal of water? The tradeoffs in this case are that too small of an area selected will be prohibitive from an analytical standpoint, whereas an area too large will be too inclusive and may overstate or understate the water stress.

Compiling Data for Reference Cases

There are a number of methodologies to estimate water use of fuel production processes that were employed in the papers that TIAX reviewed for this report. TIAX found that the results of each method were in good agreement; however, the Energy Commission should spend some time and resources confirming this further. For non-farm-related activities, research at national laboratories may be a valuable resource. TIAX has shared information with the Energy Commission regarding an existing inventory of water use requirement for various processes developed as part of a Water-Energy Nexus modeling effort at Sandia National Laboratory.

The WaterGAP2 model should be the starting point for defining water stress indices. The model includes more than 10,000 individual watersheds globally. The model consists of both a hydrological and socio-economic component that includes annual freshwater availability and withdrawals for different users – industry, agriculture, and households. Data in the model are based on the annual average data from the climate normal period (1961-1990). The model does not have a methodology to account for monthly and annual variations in water availability. Pfister et al (2009) developed a function to account for periods of increased water stress; however, the variation is described only briefly in their published research. Further investigation and communication with appropriate researchers and experts will be necessary to clarify the validity of the modification and how this could be incorporated into an analytical framework.

Weighting Factors

The relationship between the water stress index and the absolute water consumption is relatively straightforward. As such, water use does not have the same level of complexity, for instance, of the other areas considered. The Energy Commission would like to promote technologies that are not as thirsty nor situated in areas that are water-stressed. Although the relationship is straightforward, this does not imply that the relationship is linear or multiplicative. For instance, it may not be appropriate to simply multiply the water consumption of a process by the water stress index of a given area. The relationship is dependent on how the Energy Commission defines the water-stress index – if it is a linear scale, for instance, then the relationship between water stress index and water consumption is likely non-linear e.g., logarithmic or exponential. In other words, water withdrawals at the margin, toward severe water stress, may be more detrimental to water availability than the average water withdrawal.

Recommendations

To date, research has primarily demonstrated that the water requirements of bioenergy crops are high and vary considerably. Research into the water use requirements of other fuels is also developing and will need to be developed further. Ultimately, the framework to evaluate the impact of transportation fuel production on water resources should be developed in twofold approach:

1. Determine local/regional water stress indices. As discussed by Pfister et al. (2009), water stress is commonly defined by the ratio of annual freshwater withdrawals to hydrological availability. The framework should then define the various levels of water stress e.g., moderate or severe, based on this ratio. Due to the complexity of calculating the water stress index for regions, the analysis would likely be done outside of a GREET-type model. There is an existing model, the WaterGAP2 model (Alcamo, Doll et al. 2003), which is capable of calculating these indices on a river-basin scale (~10^6 ha). The sustainability analysis will likely need the indices calculated on a smaller scale e.g., catchment scale (~10^2–10^5 ha).

2. Use a GREET-type format/model to track other variables and parameters such as: water requirements, crop type, local/regional climate conditions, soil type and soil quality. Note that climate conditions must be constantly updated to understand the impacts fully, as these are likely to change over time due to natural variability and climate change.

Other factors that should be incorporated include:

- Competing local demands for water use should be characterized, as well as the value of the crop relative to its water use, as this is a primary driver in local decision making.
- The seasonality of the crop, as the water availability may not be constant over time.
- The impact on water resources must also consider crop displacement where appropriate.

Water Quality

Water quality is defined as the degree to which water meets the needs for which it is intended. In general parlance, water quality is used in reference to its suitability for drinking (e.g., potable water) in terms of purity, aroma, appearance, and taste. In this sense, the application of fertilizers, herbicides, fungicides, insecticides, and other pesticides for agricultural purposes can have negative impacts on water quality via surface water runoff or infiltration to groundwater. Because the uses to which water is put are nearly unlimited, quality can best be defined only in context with the water's intended use.

Current State of Knowledge

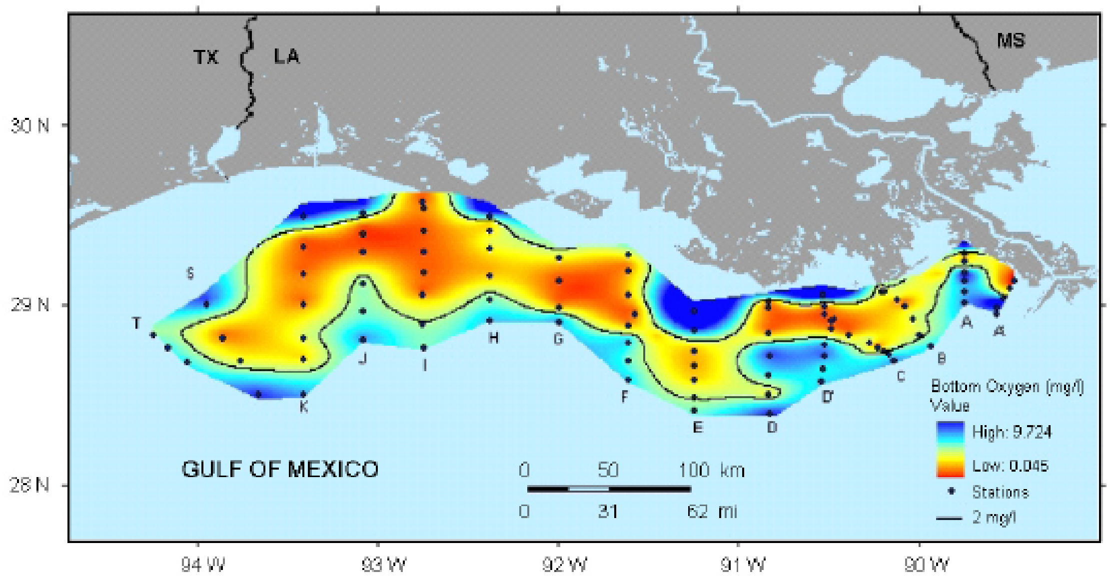
California has an extensive monitoring network to measure water quality in groundwater and surface water, managed by the State Water Resources Control Board as part of the California Environmental Protection Agency. The board manages a database of numerical water quality limits for more than 850 chemical constituents and water quality parameters. Measuring water quality, however, is considerably different from attributing observations to individual non-point sources. Generally, water quality problems are the result of the accumulation of non-point sources, which makes it difficult to attribute a change in water quality to a single activity. Standards and regulations have been developed to limit pollution and contaminants from sources such as discharge, runoff, and leakage from storage units.

The challenge in this section is to understand how the production and use of transportation fuels impact water quality directly, rather than water quality in a general sense. It is important that the authors first review the notion of water quality. The intended uses of water can result in definitions of quality that are substantially different. For example,

- Water intended for the irrigation of parks and golf courses might have considerably lower requirements for purity and taste (e.g., reclaimed water), slightly lower requirements for appearance, and still require high levels of quality for aroma (i.e., lack of smell). Thus, water might be of high quality for use in the irrigation of public landscapes if it is odorless and only slightly cloudy or discolored, even though it contains too many harmful impurities to be consumed safely by people.
- Water intended for use as a habitat of aquatic animals might have a different set of criteria for quality. These might include the temperature of the water, its flow volume (and variations in that volume), salinity, amounts of dissolved oxygen, and purity from metals and chemical contaminants (Energy Commission 2003).

Water quality impacts vary significantly across fuels. For some fuels, multimedia impact assessments have been completed, including gasoline, diesel, CNG, methanol, and ethanol. These assessments are valuable; however, they are limited to the impacts of the fuel, rather than the effects of every stage of the fuel cycle. For instance, in the case of petroleum fuels, the multimedia impact assessment does not include toxics released during the production and refining stages. Similarly, in the case of biofuels, water quality impacts from the application of fertilizers (e.g., nitrogen) and pesticides (e.g., atrazine) are not included. Both fertilizers and pesticides contribute to groundwater contamination, sediment runoff, and oxygen-starved "dead zones" i.e., hypoxia. Hypoxia is a condition characterized by low levels of dissolved oxygen caused by elevated nitrogen (N) and, to a lesser extent, phosphorous (P) loadings. These high levels of nitrogen and phosphorous can lead to algal blooms over a large area. Upon their death, and subsequent decomposition, these blooms consume extraordinary amounts of oxygen in the water, creating an environment unsuitable for most fish and other aquatic species. Today, there are an estimated 400 dead zones around the world, covering a total estimated area of about 245,000 km^2 (Diaz and Rosenberg 2008). The dead zone in the Gulf of Mexico (See Figure 6.), a result of nitrogen fertilizer runoff and transport, is an excellent example of the potential impacts related to increased nitrogen fertilizer use.

Figure 6: Dissolved Oxygen Levels in the Gulf of Mexico



Values are shown in milligrams per liter, mg/L in the Gulf of Mexico, measured on July 21-28, 2007. Increased nitrogen fertilizer application leads to run-off from farmland into the Mississippi and discharged into the Gulf of Mexico leads to hypoxia.
Source: (NRC 2008)

Other water quality hazards resulting from agricultural runoff include eutrophication and contaminated drinking water. Nitrogen and phosphorous fertilizer application rates are the main constituents for runoff and infiltration in the production of biofuels. Many feedstocks are considered based on the availability of marginal lands. The use of marginal lands is touted as a benefit because it limits GHG emissions attributable to land use change (direct or indirect) and dodges the food vs. fuel issue. However, it may have negative impacts for water quality because marginal lands may require increased fertilizer applications to increase yields. High nitrate and nitrite (NO3-N) loadings in drinking water are a human health hazard. High NO3-N concentrations also affect the health of natural systems, as eutrophication causes low- and zero-oxygen conditions. This leads to loss of marine life (e.g., fish and shellfish) and provides an environment for potentially toxic algal blooms (Nixon 1995; Jordan, Berendse et al. 1996; NRC 2008.)

The production of transportation fuels, e.g., electricity, can have unexpected and significantly negative impacts on water quality. The production of electricity and hydrogen as transportation fuels can seriously impact water quality through the discharge of water from cooling systems. This discharge sometimes contains dissolved solids such as salts and toxic metals and might threaten aquatic life with effluents that alter the temperature of creeks and streams or cause excess variation in flow volumes. The discharge compositions and rates are a function of the technology employed and the frequency of cooling tower use (Energy Commission 2003).

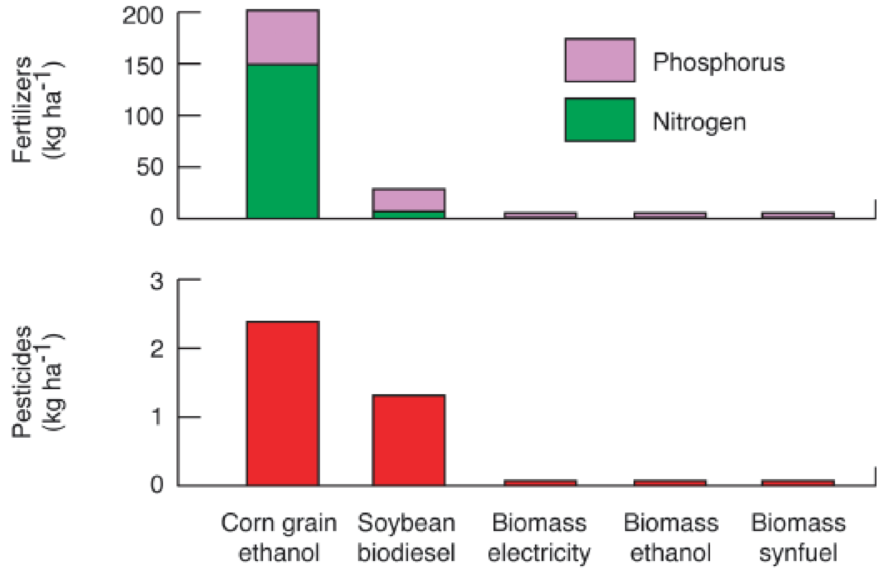
The production and marketing of petroleum-based fuels and products impact marine environments through marine tanker spills. Groundwater is affected by releases from pipelines, discharges from refineries, and spills from tanker trucks. TIAX reviewed the various impacts on water quality by examining the number of reported spills and the cost of cleanup (on a per-gallon-of-fuel-produced basis) as part of a report to the Air Resources Board and the Energy Commission (TIAX 2003). This report evaluated open ocean marine spills, marine terminal spills, pipeline spills, refinery spills, transportation spills, and leaking underground storage tank spills.

Metrics

The toxicity effects of poor water quality are well understood and there are regulations regarding drinking water in place to protect human health. However, most of these toxicity measures occur after the production of a transportation fuel, making it difficult to link the fuel production with the adverse impact on a given body of water. Less is known about the quality of water for purposes other than human consumption, such as aquatic life, wildlife, and microbial life.

Hill et al. (2006) calculated the application rate of N and P fertilizers and pesticides per unit of net energy gained from biofuel production, reported as grams of fertilizer per energy content of fuel, g/MJ (Figure 7). These impacts are related only to the application of fertilizers at the farm production processes, and do not include any impacts along the other steps in the production of fossil, bio-, and alternative fuels.

Figure 7: Fertilizer and Pesticide Applications Rates



Comparisons of fertilizer (top) and pesticide (bottom) application rates for various feedstocks; reported as U.S. averages.
Source: Hill et al. (2006)

In general, the development of metrics that capture the potential impacts of the full range of transportation fuel production on water quality is lacking in the scientific literature. In fact, a recent issue paper released by the United Nations Environmental Program (UNEP) stated that "within the small pool of research on water quality impacts from bioenergy, there are even fewer studies conducted on water quality concerns on different parts of the product cycle" (UNEP 2010). This is due in large part because problems such as nutrient-loading arise from an accumulation of different non-point sources. This makes it difficult to assess the weighted impact of fuel production on water quality issues.

Framework Development

Comparative Basis

The site-specific objectives that are used should be uniform across all transportation fuels to mitigate against the potential for confusing comparisons. There should not be mixing between objectives e.g., aquatic life criteria or human health-based objectives. If different site-specific objectives are used, an additional normative factor will have to be incorporated, which will only introduce further uncertainty.

In the event that an approach is pursued using watershed modeling, then the Energy Commission should identify a model that is suited for the analysis of impacts of transportation fuel production processes. It is important to note that these impacts may be difficult to assess in such models, as their impacts may be marginal in many cases, yielding little to no observable change in water quality.

With regard to pollutant discharges, it may be difficult to compare across pollutants. For instance, what are the water quality impacts of total dissolved solids compared to nitrogen fertilizer? The first step to characterize local or regional water quality, however, should help normalize the comparison of two production processes. Ultimately, the first step helps identify the water pollutants that should be considered in step 2. The final comparison, then, is based on the risk to water quality, rather than a comparison of pollutants.

Boundary Conditions

Different hydrological processes dominate at different scales i.e., the hilltop scale (< 1 ha), catchment scale (~102-105 ha), and river basin scale (> 106 ha), as discussed in Uhlenbrook (2007.) The spatial scale should be limited, as it is more challenging to quantify the impacts at large scales.

Pollutants can persist in the aquatic environment over different temporal and spatial scales. This persistence must be considered in the accounting stage of the analysis. To maintain a common comparative basis, the authors recommend accounting for the pollutants that will have an impact at the same hydrological scale used in the first stage. Some pollutants may have impacts much further afield, however, attributing a measurable or verifiable change in impact based on such a large hydrological scale is likely to be prohibitively challenging. If impacts are likely to have a significant impact further afield as production volumes increase, then more detailed modeling may be needed.

Compiling Data for Reference Cases

The U.S. Department of Agriculture maintains statistics on fertilizer and pesticide use at various spatial scales. There are also many literature studies that examine the amount of fertilizer application for various crops. These data will be useful in the development of an inventory for reference cases. The research performed by Hill et al (2006) is a useful starting point.

Apart from farm-based processes, industrial processes require a permit to discharge water, depending on where the facility is discharging water, e.g., subsurface, surface, etc. This reporting is similar to the reporting requirements for air quality pollutants such as VOC and NOx. The Energy Commission should work with other state, local, and regional agencies to aid in the development of an inventory of discharge pollutant statistics for various industrial and farm-related processes.

Weighting Factors

The weighting factors used for the site specific objectives will depend significantly on the policy objectives determined by the Energy Commission. As described in the document from the State Water Resources Control Board, there are several site-specific criteria that can be used, e.g., aquatic life or risk to human health (SWRCB 2003).

The weighting of pollutant discharges should be rendered unnecessary by the first step to characterize local or regional water quality. In the event that this is not the case, the Energy Commission will need to align its decision with policy goals to normalize the impacts across watersheds.

Recommendations

To develop an analytical framework to evaluate the impacts of transportation fuel production pathways on water quality, the authors suggest a twofold process, similar to the framework described in water resources.

1. Characterize the local and regional issues of water quality. The spatial scale should be limited, as it is more challenging to quantify the impacts at large scales. Different hydrological processes dominate at different scales i.e., the hilltop scale (< 1 ha), catchment scale (~10^2-10^5 ha), and river basin scale (> 10^6 ha), as discussed in Uhlenbrook (2007). There must also be a consideration of water quality thresholds. The development of thresholds will require either a) site-specific objectives, or b) local/regional watershed modeling.

a. The State Water Resources Board published a draft guidance document for the development of site-specific water quality objectives in California (SWRCB 2003). The criteria for site-specific objectives are reviewed briefly below:
    - Aquatic Life Criteria: Based on available toxicity data for any species that has reproducing wild populations in North America. The EPA has three published procedures and a number of other procedures based on proven scientific principles to establish site-specific objectives in this area.
    - Human Health-Based Objectives: These are intended to protect human health from the adverse effects of pollutants. Criteria might include fish consumption rate, bioaccumulation factors, and percentage lipid in aquatic organisms.
    - Other Objectives and Guidelines: These include wildlife objectives (i.e., birds or mammals, not aquatic life), sediment guidelines and nutrient-based objectives.

    For the purposes of the framework to evaluate the sustainability of transportation fuels, the Energy Commission can borrow from the guidance provided by the EPA for site-specific water quality objectives listed above. As an analytical framework, rather than a regulatory standard, there is considerable flexibility in the selection of site-specific objectives.

b. An alternative to site-specific objectives would be local and/or regional watershed modeling. In the event that the data and time requirements for watershed modeling are prohibitive, then the evaluation should at least consider factors such as local and regional drinking water contaminant levels and the health of local aquatic ecosystems (as measured by any number of indicators, ranging from total dissolved oxygen and sediment organic carbon to shellfish tissue chemistry and interstitial water toxicity).

2. Account for pollutant discharge at each stage of production using a GREET-type format/tool, which would be aggregated and reported on a per-unit-energy-of-fuel basis. These pollutants would include

- Fertilizers and pesticides, herbicides, or fungicides for farm production.
- Total dissolved solids and other refining effluent.

These pollutant loadings should be calculated based on factors such as crop type, soil type, climatic conditions, and technology type.

The framework might also include the comparative consequences of different types of fuel on water quality when rare or unintended events occur. For example, petroleum contamination commonly results from marine oil spills,[8] leakage from underground storage tanks, and runoff from roadway spills. Biofuels replace some of the most toxic parts of petroleum with substances that biodegrade in water fairly quickly (Neufeld 2000). Therefore, biofuels might reduce the threat from accidents and spillage and the costs associated with environmental clean-up and recovery.

Soil Quality

In general, expert consensus defines soil quality as the soil's ability to perform the following five key functions (Toth, Stolbovoy et al. 2007; USDA 2009):

- Nutrient cycling
- Biodiversity and habitat maintenance
- Physical stability and support
- Water interactions
- Filtering and buffering

Soil quality can be evaluated according to two types of baselines: 1) how an activity affects soil quality relative to its original state and 2) how an activity affects soil quality relative to its intended function. These two types of baselines can lead to different conclusions for the same activity. For example, the planting of crops may degrade soil quality relative to that of previously unused land but may improve soil quality in aspects that increase agricultural yield of the specific crops. The choice of baselines affects the definition of "soil quality sustainability" for a given activity. If soil quality is evaluated relative to its intended function, sustainability may be best defined as the suitability of the soil for continued performance of that function. If soil quality is evaluated relative to its original state, then sustainability may be best defined by the cumulative change in soil quality.

Both types of evaluation baselines reflect the same key principle: There is no absolute scale of soil quality. The sustainability of an activity in terms of soil quality can only be judged based on the inherent properties of the soil and not against one fixed standard of an "ideal" soil for all cases. While the dynamic properties of soil, such as organic matter content, are use-dependent and can change with land use practices, the inherent properties of soil, such as clay type, are use-invariant and establish the boundaries for the quality of that soil. Accordingly, there is no single set of characteristics to describe a soil that is "best" for all locations and functions.

In evaluating the sustainability of transportation fuel production in terms of soil quality, there are two relevant sets of effects. First, fuel production affects soil by changing the soil that is physically covered by production facilities. Due to construction of the facilities, underlying soil is likely to experience increased ability to provide physical stability and support, at the expense of the remaining key soil functions (nutrient cycling, maintaining biodiversity and habitat, water interactions, and filtering and buffering). Second, fuel production affects soil by changing

[8] \TIAX would be remiss if it did not mention the April 20, 2010, Deepwater Horizon disaster, named for the rig that BP was using to explore a new oil field in the Gulf of Mexico. The ensuing leakage may turn out be the largest accidental oil spill in history. For comparison, the spill will most certainly be larger than the *Exxon Valdez* spill in Alaska in 1989, which released 260,000 barrels of oil.

the soil used to grow biomass feedstocks. Whether the biomass is specifically cultivated for fuel production (e.g., corn) or uses biomass byproducts (e.g., forest trimmings), the collection of biomass from land has implications for soil quality. Both sets of effects may or may not be reversible, and the focus of this sustainability assessment framework is on soil quality changes resulting from the continuous production of biomass for fuel.

Finally, evaluations of soil quality can be measurements or assessments, a subtle difference that is often overlooked. Measurements of soil quality attempt to quantify specific metrics for physical samples. In contrast, assessments of soil quality attempt to describe the relationship between activities and soil quality. The following sections elaborate on the ties between measurements and assessments and discuss the resulting framework for assessing the soil quality sustainability of transportation fuel production.

Current State of Knowledge

While there is general consensus on the definition of soil quality and the physical metrics that describe soil quality, there is no single method for assessing soil quality as a result of potential human activities. This lack of consensus can be attributed in part to the different purposes for which various assessment methods have been developed. For example, some assessment methods, such as the Natural Resources Conservation Service Soil Quality Test Kit (USDA 2010), have been developed to monitor and increase agricultural yield of a specific site, while others, such as the Long-Term Hydrological Impact Assessment (L-THIA) (Purdue 2003), have been developed to minimize harmful effects to nearby bodies of water.

Current methods for assessing soil quality fall into five general categories:

- Guiding principles and criteria
- Qualitative scorecards
- Field test kits
- Lab-based assessments
- Practice predictors

Guiding principles and criteria set standards that activities must meet to be considered sustainable from a soil quality perspective. Various organizations have established checklists for determining the soil quality sustainability of human activities, particularly biomass production. These checklists prescribe the considerations, practices, assessments, and measurements that must be undertaken for activities to attain certain sustainability levels. The Council on Sustainable Biomass Production provides two sets of soil criteria for meeting its “silver” and “gold” levels that categorize activities based on whether participants have made commitments such as monitoring soil nutrients, retaining biomass materials for erosion control, or establishing comprehensive land management planning (CSBP 2009). While useful for encouraging sustainable activities, guiding principles and criteria do not differentiate the degrees to which commitments are implemented and therefore do not allow for quantitative comparison of activities.

Qualitative scorecards are used on specific sites by land managers to observe and monitor soil quality changes over time. The scorecards offer a consistent, albeit subjective, method of recording soil observations without requiring specialized equipment. For example, land managers may rate water infiltration of their soil on a scale from "Crops wilt quickly after water events" to "Crops curl or wilt but come back quickly" to "Crops tolerate droughty conditions"(USDA 2000). Qualitative scorecards are developed for specific areas based on their individual soil quality concerns.

Similar to qualitative scorecards, field test kits are used by land managers to monitor their specific sites. The test kits are designed to be simple to use and to offer a way to not only observe, but also quantify soil metrics. Based on physical field samples, land managers conduct tests such as the Soil Respiration Test, Bulk Density Test, Electrical Conductivity Test, pH test, and Earthworm Test (USDA 2010). Field test kits are valuable tools for evaluating soil quality changes in specific locations over time but may not be appropriate for comparing different locations, particularly because the quality of soil in different locations is constrained by inherent baseline properties.

Lab-based assessments, such as the Soil Management Assessment Framework (SMAF) (USDA 2009), are intended to help land managers select the appropriate metrics to measure and analyze their sites. They extend the functionality of field test kits by prescribing more detailed evaluations of soil quality metrics. Land managers enter in specific characteristics of their soil, such as geography, soil type, and primary land management goal, and are given sets of metrics to measure to ascertain soil quality. The results of these measurements may be aggregated into indices that can be used by land managers for comparisons over time.

Practice predictors establish quantitative relationships between soil quality and various activities. For example, the Soil and Water Eligibility Tool (SWET) is used by the United States Department of Agriculture's Conservation Security Program to correlate various land management practices with measured soil and water quality (USDA 2008). Users of the tool enter information about their practices, including tillage intensity, fertilizer application rates, and crop rotations, to receive quantitative scores predicting their corresponding soil quality. These scores have been shown preliminarily to correlate with measured soil quality metrics, although further calibration of the tool has been suggested (Andrews, Karlen et al. 2008). Other tools include the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) and the Water Erosion Prediction Project (WEPP), which also look at land use practices to predict soil quality (USDA 2009; USDA 2009). However, RUSLE2 and WEPP focus solely on erosion by water, making it not useful for general soil quality sustainability. Similarly, tools such as the Environmental Policy Integrated Climate (EPIC) model, the Long-Term Hydrological Impact Assessment (L-THIA), and the Nitrate Leaching and Economic Analysis Package (NLEAP) focus narrowly on specific subsets of soil quality evaluation (Shaffer, Halverson et al. 2002; Purdue 2003; NASA 2006).

A subset of practice predictors includes multi-factor sustainability indices. These indices examine a range of inputs to arrive at numerical indices that allow for the comparison of land use activities. Soil-related concerns may be weighted differently depending on the purpose of the index. For example, the Soil Sustainability Index (SSI), used by the Joint Research Centre of the European Commission, evaluates not only soil function, but also threats to soil function, including compaction and landslides. SSI is one of the most comprehensive soil assessment indices and takes into account soil quality, soil threats, and soil response properties. Each factor consists of a mathematically described relationship to other factors in the sustainability index. However, to use the index, detailed experimental data for the specific soil under varying conditions are required, making the index less useful for transportation applications in which upstream feedstocks may come from multiple, unstudied sources. In theory, multifactor sustainability indices are good candidates for assessing the sustainability of transportation fuels, but the actual applicability and usefulness of specific indices will depend on the purpose for which they were developed and the availability of data required to calculate the indices.

A summary of key existing soil quality assessment tools is presented in Table 4. This list is not intended to be all-inclusive but instead offers a sampling of currently available tools.

Broadly speaking, the majority of current studies and tools available for assessing soil quality focus on site-specific changes over time. Soil quality is well-understood in terms of measurable metrics for physical plots of land and is sufficiently advanced to justify being included in an analytical framework. However, the application of this base of soil quality knowledge to assessing the sustainability of transportation fuels is sparse and will require further development.

Table 4: Summary of Key Existing Soil Quality Assessment Tools

	Assessment Tool	Description	Tool Access
Guiding Principles & Criteria	Council on Sustainable Biomass Production Standard	Specifies practices, assessments, and measurements that activities must address to be considered sustainable (In progress)	http://www.csbp.org/files/survey/CSBP_Draft_Standard.pdf
	Roundtable on Sustainable Biofuels Guidelines	Describes issues and impacts that activities must address to be considered sustainable	http://cgse.epfl.ch/webdav/site/cgse/shared/Biofuels/Version%20One/Version%201.0/ESIA%20Annex%20-%20Soil%20specialist%20guidelines.pdf
Qualitative Scorecard	Soil Quality Card	Allows land managers to select and monitor metrics to determine changes in soil quality over time without the aid of technical or laboratory equipment	http://soils.usda.gov/sqi/assessment/sq_card.html
Field Test Kit	Soil Quality Test Kit	Allows land managers to quantitatively measure key soil quality metrics in the field	http://soilquality.org/tools/test_kit.html
Lab-Based Assessment	Soil Management Assessment Framework (SMAF)	Directs land managers to measure specific soil quality metrics most relevant to their sites	http://soilquality.org/SoilQualityWebsite/SoilQualityMainServlet?sequenceCode=SoilQualityIndex
Practice Predictor	Environmental Policy Integrated Climate (EPIC)	Assesses effect of erosion on productivity of various crops	http://gcmd.nasa.gov/records/EPIC.html
	Long-Term Hydrological Impact Assessment (L-THIA)	Predicts annual runoff for various land uses	http://cobweb.ecn.purdue.edu/runoff
	Nitrate Leaching and Economic Analysis Package (NLEAP)	Determines potential nitrate leaching associated with agricultural practices	http://ecobas.org/www-server/rem/mdb/nleap.html
	Revised Universal Soil Loss Equation (RUSLE2)	Predicts average erosion by water for various land uses	http://www.ars.usda.gov/Research/docs.htm?docid=18095
	Soil and Water Eligibility Tool (SWET)	Correlates land management practices with measured soil and water quality	http://www.pa.nrcs.usda.gov/programs/CSP/Tools/Soil_and_Water_Eligibility_Tool_v.4.xls
	Soil Sustainability Index (SSI)	Combines known relationships for soil quality, soil threats, and soil response properties to derive a single sustainability index value	http://eusoils.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/other/EUR22721.pdf
	Water Erosion Prediction Project (WEPP)	Predicts erosion based on soil parameter inputs	http://www.ars.usda.gov/Research/docs.htm?docid=10621

Source: TIAX LLC

Metrics

In the context of the two major review criteria for a sustainability framework, evaluating soil quality based solely on individual metrics can be misleading. Soil quality metrics are interrelated through a very complex set of relationships, and isolating specific metrics for the purposes of determining sustainability can inaccurately represent these relationships.

Infiltration, the downward entry of water into soil, is one measure of soil quality; it increases with increasing pore size, which is determined by the degree of aggregation of soil particles, which in turn is affected by the level of soil organic matter. Decreased infiltration causes ponding of water on the soil surface, which results in poor soil aeration, which leads to poor root function, decreased plant growth, reduced nutrient availability, decreased soil strength, and increased erodibility (USDA 2009). The complexity of such relationships suggests that examining soil quality metrics individually may not make sense, both because a snapshot approach may not capture the ever-changing soil dynamics and because it is difficult to isolate an exclusive set of metrics applicable to a range of activities to be assessed.

It may be tempting to define an "ideal" quantitative assessment of soil quality that comprehensively captures all of the known soil quality metrics. Such an assessment may require that each metric is experimentally measured before and after the specific activity in question, at a specific site, to establish the true effect of the activity on soil quality at the proposed site. However, in addition to its infeasibility for the wide range of activities and sites under consideration, the specificity challenges make this kind of assessment impractical and potentially paralyzing.

Therefore, a promising approach that many of the existing assessment tools have adopted is the use of land management practices as proxies for individual metrics. Land management practices have the advantage of being directly relatable to human activities while also reflecting soil quality. Studies in the literature can provide evidence for the correlations between specific practices and soil quality metrics. Land management practices can capture a broader picture of soil dynamics than measurements of individual metrics alone. For the purpose of assessing the sustainability of transportation fuels, land management practices offer a way to compare the effect on soil quality of a range of feedstocks, geographies, and fuel pathways.

Using land management practices to evaluate soil quality meets the first review criterion of measurability, quantifiability, and verifiability by being fundamentally tied to soil quality metrics. Adopters of these practices would be able to provide not only records that the practices were being followed, but also physical samples that could be measured and quantified at regular intervals by third parties for verification. The initial practice-based assessment would determine the sustainability of the activity, and the measurement-based verification would confirm that the activity's ongoing positive, negative, or neutral effect on soil quality. As with other impacts of a sustainability assessment framework, development of specific definitions and gradations in land management practices would be based on publicly accessible, peer-reviewed data and stakeholder input.

Using land management practices to evaluate soil quality also meets the second review criterion of consensus among experts regarding their utility as an assessment tool. Practice predictors have been developed for and used widely by major organizations, including the United States

Department of Agriculture. Their continued updating and incorporating the most recent data available reflects the agreement within the expert community that land management practices are valuable tools to evaluate long-term sustainability.

Framework Development

Drawing from the advantages and disadvantages of existing assessment tools, a useful and viable analytical framework for evaluating soil quality aspects of sustainability is one based on land management practices. As discussed above, because it is not always possible or desirable to use soil metrics to assess soil quality, an analytical framework based on land management practices reflects the relationship between an activity and its effects on soil quality indicators, without requiring the direct and ongoing comparison of soil sample measurements. The aim of this framework is to distill out the key drivers of soil quality; even if a particular metric is not specifically addressed, its role in soil quality should be captured and indirectly represented by the set of land management practices.

Comparative Basis

The evaluation of soil quality sustainability will be driven by relative impacts, and using a baseline that has small land cultivation impact will give very different results than using a baseline that is land-intensive. A baseline that is well established may have small land cultivation impact, not necessarily because it is desirable from a soil quality perspective, but rather because the soil quality impacts are likely to have already been made. This situation is generally true for conventional transportation fuels, as well as alternative fuels such as natural gas that have extensive existing infrastructure, albeit for other purposes at present. In contrast, fuels based on dedicated energy crops, including corn, switchgrass, and short rotation woody crops, are likely to require the conversion of land previously unused or used for other purposes. In all cases, a baseline must be established as to where to draw the line of soil quality impacts: Will impacts already made to soil quality be considered? Will the soil quality impacts of alternative uses of the same land be considered? To some extent, the selection of a baseline against which all fuels are evaluated will require a determination regarding the reversibility of soil quality impacts. Furthermore, to ensure that comparisons across soils and activities are made on a common basis, consideration needs to be given to whether certain practices are fundamentally possible in each case such that activities are not inappropriately penalized for practices that are not achievable.

Boundary Conditions

Because soils are part of dynamic ecosystems that may or may not adapt to change over time, it is important to establish the time frame in which impacts are being evaluated. Spatially, the scope of the soil sustainability assessment should be defined in terms of which land areas will be considered for soil quality impacts. For example, an assessment can be bounded only by the land used to grow the fuel feedstock, or it can be bounded to include both the feedstock land and the land under the fuel production facility. Temporally, the scope of the soil sustainability assessment should be defined in terms of the period over which soil quality impacts will be evaluated. As dynamic systems, soils require some amount of time to fluctuate and assimilate changes; examining soil quality on too short a timescale may exaggerate the impacts, while examining soil quality on too long a timescale may cause important causal relationships or windows of opportunity to be missed. Reversibility of soil quality impacts plays a role in these considerations as well, given that in some cases, severely degraded or toxic soil may not ever be restored, even with long recovery times.

Compiling Data for Reference Cases

To develop a tool to assess the soil quality sustainability of the various land management practices used in an activity, an inventory of the effects of all potential practices must first be established. At a minimum, the inventory should include practices relating to: tillage, soil cover, crop rotation, soil traffic, nutrition and fertility management, and pest management. Within each of these parameters, there are many specific actions that can be taken, such as minimum tillage, use of cover crops, crop rotation, use of designated traffic patterns, soil nutrient testing, and use of pest-resistant crop varieties. Starting with established land management practices such as those in the USDA Soil and Water Eligibility Tool, a full list of potential land management practices and their effects on soil quality should be developed. This list will serve as a resource to understand how important certain practices are and inform subsequent judgments about which practices are necessary to include in a sustainability evaluation tool.

Weighting Factors

As described through the inventory of land management practices and their effects on soil quality, every practice will impact soil quality differently. From the perspective of measurable metrics, such as soil organic carbon and water capacity, certain practices will have a greater effect on soil quality than others. More critically, from the perspective of value judgments and policy goals, certain practices will be more important to soil quality than others. Depending on which aspects of soil quality are deemed to be most relevant to sustainability, more weight may be given to practices that most affect those aspects. For example, while recognizing that most aspects of soil quality are interrelated and that one practice will affect multiple aspects, if erosion is a primary concern, then practices relating to soil cover may be weighted more heavily than those relating to pest management practices. Because an evaluation of sustainability will be subjective based on the priorities of tool developers and policy makers, it is important to define the relative importance of each of the possible land management practices.

Recommendations

Drawing from the advantages and disadvantages of existing assessment tools, a useful and viable analytical framework for evaluating the impact of transportation fuels on soil quality, the authors recommend a similar twofold approach. Note that the framework proposed here applies primarily to activities that are biomass-based and dynamically change the soil. Soil quality changes caused by the physical siting of a production facility are not included here.

1. Identify the most pertinent land management practices that reflect impacts on soil quality. An analytical framework based on land management practices reflects the relationship between an activity and its effects on soil quality indicators without requiring the direct and ongoing comparison of soil sample measurements. The aim of this framework is to distill out the key drivers of soil quality; even if a particular metric is not specifically addressed, its role in soil quality should be captured and indirectly represented by the set of land management practices. This list of land management practices in Table 5 forms the basis of the framework for evaluating the soil quality sustainability of transportation fuel production activities.

Table 5: Land Management Practices

Parameter	Scale	
	Minimum	Maximum
Tillage Intentional disturbance of soil surface expressed as percentage of soil covered with crop residue/cover crop after planting	0%	100%
Soil cover Residues, composts, other mulch materials, and cover crops expressed as percentage of material not harvested	0%	100%
Crop rotation Growth of different crops in sequential seasons on the same land expressed as number of species planted	1	(No maximum)
Soil traffic Level of soil compaction caused field operations	☐ Close monitoring of soil moisture prior to all field operations ☐ Controlled, designated traffic patterns	
Nutrition and fertility management Monitoring and application of soil amendments	☐ Testing soil to determine the nutrient supplying power of the soil ☐ Determining recommended amounts of nutrients needed to produce the desired yields ☐ Analyzing nutrient content of and accounting for nutrient inputs from legumes, cover crops, manure, composts, irrigation water, previous crops, or soil organic matter ☐ Applying manures or composts at recommended rates and based on the limiting nutrient to meet but not exceed crop nutrient needs, according to soil tests ☐ Applying the additional inorganic nutrients as needed according to soil tests	
Pest management Monitoring and application of pest controls	☐ Using pest-free seeds, certified seeds ☐ Using protective seed treatments ☐ Using disease-free transplants or rootstocks ☐ Cleaning tillage and harvesting equipment between fields ☐ Scheduling irrigation to avoid situations conducive to disease development ☐ Using pest-resistant crop varieties ☐ Using trap crops ☐ Using biological pest controls ☐ Scouting and using economic thresholds before treating pests (weeds, insects, disease) ☐ Using spot spraying, banding, or other reduced use of chemical ☐ Using hand hoeing ☐ Monitoring field for potential problems constantly ☐ Removing or plowing down infested plant material	

Source: USDA Soil and Water Eligibility Tool (USDA 2008)

2. Develop a composite index based on land management practices. To use the framework, the evaluator determines how the activity applies to each of the parameters identified in Table 5. The individual scales from the parameters can then be assessed separately or aggregated into a soil quality index for comparison with other activities. An index would essentially apply numerical scores to the scales (as percentages, absolute numbers, or number of practices selected from the checklist) then apply weighting factors to the parameters to arrive at a final score:

$$\textit{Soil quality sustainability} = \sum_i w_i s_i$$

where w is a weighting factor, s is a score for the ith parameter. It will be the task of developers of the analytical tool based on this framework to make judgments on the exact definitions of individual scales and the relative weighting of each parameter. For instance, tool developers, with stakeholder input, may choose to create thresholds rather than a continuous numerical scale for tillage, using descriptors such as no-till, conservation-till, reduced-till, and intensive-till instead of percentage of soil covered. In another example, tool developers may decide that toxicity implications of pest management are more critical to California sustainability than the greenhouse gas implications of nutrient amendment application and thus choose to weight these parameters accordingly. The practices represented by the scales in Table 5 are not necessarily achievable or desirable, and the set of land management practices selected for a specific activity must be technically and economically appropriate to its operations and site.

The suggested framework essentially creates a sustainability index based on possible land management practices and their relative effects on soil quality. Similar to SWET, this framework establishes hierarchies for each major type of land management practice to describe the spectrum of possible options for a particular activity (Table 5). The list of land management practices is derived from multiple sources (Feenstra, Ingels et al. 1997; Earles and Williams 2005; 2009; Network 2009; USDA 2009; Stahlbush 2010) to reflect an agreement among regulators, scientists, and farmers on the evaluation of soil sustainability. In some cases, such as the total number of crop rotation species where more is better, there is no maximum limit on the evaluation scale. In other cases, the scale consists not of continuous numerical values, but rather discrete checklists of potential practices.

Perhaps more than in the other areas included in this report, it will be essential to audit and verify the land management practices put in place. Although this step is ideal for each of the sustainability impacts evaluated in this report, auditing and verification of activities are particularly important for soil quality. These are more important for soil quality because of the focus on land management practices. Soil quality depends on a complex set of interactions that may not behave as intended during planning phases. Each soil quality parameter has tradeoffs with other parameters and other sustainability impacts, and these tradeoffs may not be apparent immediately. For example, reduced tillage decreases water requirements, reduces erosion, and maintains soil fertility but may increase the amount of herbicide required to suppress weeds and disease. It will be essential to verify the level of sustainability achievable in actual sustained operations relative to intended land management practices.

Biodiversity

Biological diversity, or biodiversity, can be defined as the totality of genes, species, and ecosystems of a region. It reflects the richness, variety, abundance, and interactions of species in the region. Interest in biodiversity is fundamentally motivated by the global loss of diversity (Hillebrand and Matthiessen 2009). A key goal is to understand how human activities affect biodiversity and ecological function, with the ultimate purpose of altering human activities as necessary for preserving ecological function.

Especially for production of transportation fuels, relating biodiversity to sustainability is complex for several reasons. First, biodiversity, as measured by a variety of species indices (discussed further below), is dependent on ecosystem health. The other environmental sustainability factors that are considered in this report – water use, water quality, and soil quality – are all integral elements to maintaining biodiversity and ecosystem function, in addition to other elements such as air quality. Even greenhouse gases, as the driver for climate change, have a significant impact on biodiversity. Because biodiversity is a confluence of these other environmental factors, it is difficult to capture the impacts without extensive analysis.

Secondly, biodiversity is not necessarily static. For example, species may change spatially (the migration of species from one area to another) and temporally (the change in population over time and at different times of the year). The ecological complexity underlying biodiversity suggests that capturing the biodiversity effects of fuel production requires more than a one-time measurement of biodiversity metrics.

Thirdly, human understanding of the impacts of transportation fuel production on biodiversity is limited. There is a qualitative understanding, for instance, that fuel production may have some impact on biodiversity through issues such as habitat destruction, climate change, deterioration of water quality or air quality, and soil quality. It is possible to determine the footprint of a proposed production facility, but the facility's activities will likely have a broader impact than the impact on the immediate plot of land on which it is sited. Given the interconnectedness of organic and inorganic elements in an ecosystem, making changes to one part of the system may have unforeseen effects on the rest of the system.

Finally, the end goal of evaluating biodiversity sustainability is to determine the impact of fuel production. A question remains as to what is being impacted that is of concern. Biodiversity may be one aspect of an ecosystem that is impacted by fuel production, but ecological function may ultimately be the potentially more relevant aspect. The current state of knowledge in this field is still evolving to understand the ties between biodiversity and ecological function and will continue to have implications for how sustainability is evaluated for transportation fuels.

Current State of Knowledge

The National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA) are an excellent launching point for a discussion of biodiversity. These legislative initiatives require projects that have the potential of significant environmental impacts to identify ways that environmental damage can be avoided or significantly reduced when feasible and disclose to the public the reasons why a project was approved if significant environmental effects are involved. The analysis of a project usually takes the form of an environmental impact report (EIR), environmental impact statement (EIS), negative declaration (ND), or environmental assessment (EA).

Neither NEPA nor CEQA clearly quantifies what constitutes a significant environmental impact (as it applies to the magnitude of an impact such as to a species' population, habitat, or range). CEQA defines "significant effect on the environment" as "a substantial, or potentially substantial, adverse change in the environment" (§21068). Under CEQA Guidelines Section 15065, a project's effects on biotic resources are deemed significant if the project/activity would:

- Substantially degrade the quality of the environment.
- Substantially reduce the habitat of a fish or wildlife species.
- Cause a fish or wildlife population to drop below self-sustaining levels.
- Threaten to eliminate a plant or animal community.
- Substantially reduce the number or restrict the range of an endangered, rare or threatened species.
- Eliminate important examples of the major periods of California history or prehistory.

CEQA also states the need to assess impacts in the project/activity that has a substantial adverse effect, either directly or through habitat modifications on any species identified as a candidate, sensitive, or special-status species in local or regional plans, policies, or regulations, or by the California Department of Fish and Game (CDFG), or the U.S. Fish and Wildlife Service (USFWS).

Therefore consultation with CDFG and USFWS is required if the project/activity may result in effects to endangered or threatened species. The consultation process helps determine whether a project would jeopardize the continued existence of an officially listed or candidate species under environmental laws such as the California or the Federal Endangered Species Act.

Although neither CEQA nor NEPA was promulgated with the sole intention of preserving biodiversity, they both represent an excellent qualitative framework to conservation and preservation of biodiversity. As these discussions transition to a more research-oriented approach to understanding biodiversity, it is important to note that biodiversity is most commonly measured on an ordinal scale where "more" simply is better and "less" is worse. The research team cannot yet determine how much more is required to be better, or how much less will result in a detectable worse. The lack of higher and more precise scales of measurement (interval and ratio scales) reflects both the youth of this field of study and the complexity of the construct of biodiversity. To date, most research into biodiversity has used measures that were specific to the research situation; measures that cross a variety of situations have yet to receive consensus and broad acceptance.

A wealth of knowledge exists on biodiversity metrics for specific ecosystems. The geographic component of biodiversity, highlighting its location-specific nature, has been acknowledged by researchers (Buckland, Magurran et al. 2005). Loss of biodiversity has been shown to generally reduce ecosystem process rates (Hooper, Chapin et al. 2005; Balvanera, Pfisterer et al. 2006; Cardinale, Srivastava et al. 2006), and these effects become stronger over time (Cardinale, Wrightt et al. 2007; Stachowicz, Best et al. 2008). Additionally, loss of biodiversity affects certain, but not all, aspects of ecosystem stability (Hooper, Chapin et al. 2005; Balvanera, Pfisterer et al. 2006).

To date, much of the research on biodiversity has focused on species richness metrics. For example, the Convention on Biological Diversity, a legally binding international treaty, established a goal "to achieve […] a significant reduction of the current rate of biodiversity loss at the global, regional, and national level."

The implication of focusing on number and abundance of species is that biodiversity has been considered primarily in the context of regulating and maintaining diversity.

The expansion of oil palm plantations in Southeast Asia has sparked an interest in understanding the impacts of forest conversion and peat conversion on biodiversity. Oil palm has been a very profitable crop for poor rural communities and has spurred investment and development in Indonesia, Malaysia, and Thailand. Oil palm plantations are generally the result of wholesale land clearing and habitat destruction, as opposed to a selectively logged forest. In other words, oil palm plantations are almost devoid of forest-dwelling species (Bruhl and Eltz 2010; Koh and Sodhi 2010; Wilcove and Koh 2010). Bruhl and Eltz (2010) found species richness for ants varied by a factor of 5 between primary forest and oil palm plantations, noting further that their sampling method is likely to underestimate the true diversity of ground-dwelling ants in forest habitats. It is important to note that palm oil can be used for many products, not just biofuels. The threat to biodiversity posed by oil palm cultivation is clear; however, there may be challenges in attributing habitat loss directly to fuel production pathways considering the multiple uses of palm oil.

More recent research has shifted focus to examining biodiversity effects on ecosystem function (Hillebrand and Matthiessen 2009). In essence, the overarching framework for evaluating biodiversity has changed from considering maximum biodiversity as the end to considering ecosystem function as the end, where biodiversity is one means to that end. This shift asks the underlying questions of why people want to prevent further biodiversity loss and what exactly is affected by biodiversity loss.

Research in the area of biodiversity – in general, not as it applies to transportation fuels specifically – is focused on the need to examine whether the proposed links between diversity and ecosystem function are both predictable and relevant in complex natural environments (Hillebrand and Matthiessen 2009). Furthermore, although the general trends between biodiversity and ecological function have been established, these relationships have not been quantified. These trends may not be applicable beyond the studied scales or ecosystems, and the application to transportation fuel production has not yet been studied.

Metrics

Current research generally characterizes or measures biodiversity using various indicators species, or species abundance as measured over a given area. Some common definitions are included here:

- **Species richness** – The measure of species richness is the least sophisticated of the methods available (but probably the most common). It is the quantification of the number of different species in a specified region/area.
- **Simpson index** – Simpson's diversity index (species diversity index) is used in ecology to account for the number of different species present, as well as the population of each species. The Simpson index represents the probability that two randomly selected specimens in a habitat belong to the same species.
- **Shannon-Wiener index** – The Shannon-Wiener index measures diversity in categorical data. It treats species as symbols and their relative population sizes as the probability. The index is increased either by having more unique species or by having a larger population of each species.
- **Alpha diversity (α-diversity) index** refers to diversity within a particular area, community, or ecosystem and is measured by counting the number of species within the ecosystem. This can be measured by counting the number of distinct groups of organisms within the ecosystem.
- **Beta diversity (β-diversity) index** is the species diversity between ecosystems; this involves comparing the number of species that are unique to each of the ecosystems. It gives the rate of change in species composition across regions/areas.
- **Gamma diversity (γ-diversity)** indicates overall diversity of species for different ecosystems within a region. It refers to the total species richness over a large area or region. It is the product of the α-diversity of component ecosystems and the β-diversity between component ecosystems.
- **The Mean Species Abundance (MSA)** is an index that calculates the mean trend in population size of a representative cross section of the species. This index was used with the Convention on Biological Diversity (CBD) 2010 indicator for species abundance. The MSA addresses homogenization by dealing only with the original species in a particular region/area. This method attempts to avoid the increase in the opportunistic species masking the loss in the original species.

Measurements of biodiversity, the most common of which is species richness, do not give the complete picture of an ecosystem. Simply counting the number of species in an ecosystem does not account for species variability or its contribution to ecosystem properties. Furthermore, it does not distinguish between species that may be more or less important in the sustainability of an ecosystem. Important attributes missed by species-based measures of diversity include:

- Abundance—how much there is of any one species.
- Variation—the number of different species over space and time. For understanding population persistence, the number of different varieties in a species in a population provides more insight than species richness.
- Distribution—where quantity or variation in biodiversity occurs. For many purposes, distribution and quantity are closely related and are therefore generally treated together under the heading of quantity.

The Eco-indicator 99 method (Goedkoop and Spriensma 2001) measures terrestrial ecosystem quality using units of potentially disappeared fraction of species (PDF). PDF values are assessed as the vulnerability of a vascular plant species biodiversity (VPBD). Pfister et al. (2009) considered net primary production (NPP) to be a proxy for ecosystem quality. They then tested the relationship between NPP and VPBD and based on the statistical correlation, correlated NPP with PDF. They used this correlation as a proxy to determine damages to ecosystem quality resulting from water withdrawals.

Framework Development

Biodiversity is the most challenging area of impact considered in this report to incorporate into an analytical framework. This is based largely on two factors: the complexity of the issue and the lack of data in the field. To reiterate a point discussed previously, one of the goals of the analytical framework is to separate or breakdown each area of impact into its constituent parts. Biodiversity is particularly complex because it is dependent on so many factors – water quality, air quality, ecosystem health, habitat preservation, etc.; this complexity feeds directly into the lack of data available. Although there are many measures of species richness, there is not as clear an understanding of thresholds for biodiversity as there is in other fields. To date, one's understanding of biodiversity is essentially binary: a high level of biodiversity is good and no biodiversity can be bad. People lack an understanding of the more nuanced positions between these two extremes.

Apart from the challenge of developing an appropriate framework to assess the impacts of fuel production on biodiversity, there is an argument to be made that it is unnecessary. This is not to say that biodiversity is not of great importance, but that biodiversity is captured in other considerations. For instance:

- CEQA and NEPA legislation require an analysis of environmental effects on a qualitative scale. CEQA specifically mentions impacts on at-risk species through direct action or habitat modification.
- The accepted methodology for determining the lifecycle GHG emissions for a fuel pathway includes, where appropriate, direct and, more recently, indirect land use change. One could argue that any large-scale habitat loss (a proxy for biodiversity in this case) would be captured in this analysis as GHG emissions, thereby negating any advantage the fuel pathway may have otherwise.
- The biodiversity of aquatic life (and some wildlife) is related to water quality, water use, and soil quality – each of which is simpler (but not simple) to incorporate into an analytical framework.

Incorporating biodiversity into an analytical framework may be onerous, and there are likely limitations of existing data. Despite these arguments, the overwhelming importance of biodiversity requires that researchers move forward in the development of an analytical framework. Based on TIAX's research, the science related to biodiversity is uncertain and the impacts not as well understood as the other areas included in this report; however, as the field evolves, the analytical framework should adapt as appropriate. Similarly, it is useful to review some of the criteria and indicators that have been proposed to manage biodiversity.

The World Resources Institute in Washington, D.C. lists the criteria for effective ecological indicators as being able to (WRI 2005):

- Provide information about changes in important processes.
- Be sensitive enough to detect important changes but not so sensitive that signals are masked by natural variability.
- Be able to detect changes at the appropriate temporal and spatial scale without being overwhelmed by variability.
- Be based on well-understood and generally accepted conceptual models of the system to which it is applied.

This gives the qualities of the information necessary, but not the parameters needed to be measured. A workshop that sought to develop a common set of biodiversity indicators across different land uses and multiple scales that can be used to measure success in achieving biodiversity objectives came up with the following indicators as the most important and meaningful (OSU 2002):

- Ecosystem extent (distribution of native habitats relative to modified ones)
- Landscape pattern (degree of fragmentation of native habitats)
- Number, proportion of at-risk native species
- Distribution and extent of invasive species
- Amount, distribution of riparian vegetation
- Water quantity, availability for ecological needs
- Water quality, using index of aquatic integrity that includes biological factors

Comparative Basis

The analytical framework to evaluate transportation fuels should consider biodiversity on a marginal basis. This is due in part to the complexity of determining an average impact of fossil fuel production on biodiversity. The biodiversity impacts of petroleum and natural gas exploration over the last 150 years are likely significant, particularly considering the amount of extraction and exploration that was conducted prior to modern environmental legislation e.g., NEPA. Determining these impacts with a high degree of certainty, however, is impossible. The challenge of using a marginal basis, however, is that the habitat loss and other biodiversity impacts from the previous 100 years of petroleum and natural gas exploration and infrastructure development is discounted. This problem is more policy-oriented than analytical; as such, TIAX respectfully defers to the Energy Commission to reconcile the issue of accounting for the legacy impacts of fossil fuel production and use on biodiversity without discounting them entirely.

The composite of biodiversity indices employed by the Energy Commission should be based on collaboration with subject area experts. Research indicates that global hotspots of species richness are not congruent with endemism or threat (Orme, Davies et al. 2005), which requires a composite of indices be used to ensure that biodiversity is indeed captured at the selected scale. (See below.) The selection of indices will ultimately be driven by factors such as data availability and data reliability.

The variables and parameters employed to represent threats to biodiversity should be selected based on their uniform applicability across fuels. At the early stages of development, it may be appropriate to use a simple footprint as a proxy for threat to biodiversity; however, this may be too simplistic. TIAX suggests the development of fuel pathway case studies to identify key threats to biodiversity and how they are related.

Boundary Conditions

The appropriate spatial scale to consider biodiversity will likely be at lower resolutions based on availability of species richness maps, and the congruence of biodiversity indices (Orme, Davies et al. 2005).

Compiling Data for Reference Cases

Raw data for biodiversity indices are available from various sources (e.g., NatureServe, the Global Biodiveristy Information Facility, the U.S. Fish and Wildlife Service Threatened and Endangered Species Database System, or the California Natural Diversity Database).

Compiling data for biodiversity will be difficult because there are multiple types of species richness. The task will be further complicated based on the species richness maps used. Graham and Hijmans (2006) created richness maps in California for terrestrial amphibians and reptiles. They developed several different species richness maps: point-to-grid maps, expert-drawn maps, and maps obtained through species distribution modeling. They found that the correlation between maps was good at lower spatial resolutions (i.e., 50 km) but concluded that, even in well-studied areas such as California, different data sources can lead to dissimilar maps of species richness. This will likely be a significant barrier to developing a composite of biodiversity indices that can be incorporated into an analytical framework with reasonable levels of uncertainty.

Based on the literature search, the data and variables of biodiversity, as they relate to fuel production processes, are the sparsest. There is a considerable amount of research related to biodiversity; however, little of it is dedicated to understanding the biodiversity impacts of transportation fuels. The recent surge in government support for biofuels across the globe has generated interest in the area; however, this research is generally limited.

Weighting Factors

The Energy Commission should consult with subject area experts in the field of biodiversity to determine appropriate weighting factors.

Recommendations

The authors recommend a twofold approach, similar to what was proposed in the water resource and water quality sections:

1. Determine an appropriate composite of biodiversity indices. This metric should be a composite of the indices described above. In fact, recent research demonstrated that global hotspots of species are not congruent with endemism – a species characterized as being native or restricted to a certain area – or threat (Orme, Davies et al. 2005). In other words, an index for one of these measures of biodiversity has limited utility and is only a snapshot of a larger picture. One of the main challenges in the development of this part of the framework will be determining appropriate boundary conditions or the scale of the problem. This in turn will be a function of resources (e.g., time and money) and data availability.

Raw data for biodiversity indices are available from various sources (e.g., NatureServe, the Global Biodiversity Information Facility, the U.S. Fish and Wildlife Service Threatened and Endangered Species Database System, or the California Natural Diversity Database).

2. Define and characterize variables that impact biodiversity and account for these variables along the entire fuel production pathway. There are many factors that negatively impact biodiversity – including excessive water withdrawals, water quality, air quality, and climate change. Other metrics, such as NPP, could be used as a proxy for biodiversity or habitat loss. In the case of the latter, a simple footprint approach, measured in area (km^2), could be used at each stage of the fuel production lifecycle. As was the case in the first step, this exercise will require the balancing of limited resources and accuracy or validity. Another issue in this area is a lack of consensus regarding what metrics, proxies, or variables are an accurate measure of biodiversity impacts. As the science evolves, however, so too should the framework.

CHAPTER 4: Conclusions and Next Steps

The most prominent theme from the authors' research into each of the areas of impacts is the importance of local and regional conditions. This represents a significant shift from the analytical approach to evaluate the global warming impact of transportation fuel production pathways. The accounting of energy inputs and outputs in the fuel production pathways, although challenging, is comparatively straightforward. This is due in large part to the global nature of climate change.

Despite the localized nature of each area of impact, TIAX has developed recommendations for the development of a framework in each case. In the case of water resources, water quality, and biodiversity, the research team recommended a twofold approach that can be generally described as follows:

1. Define the local/regional impacts as a stress or health index at each stage of the fuel production pathway.
2. Define a variable, or set of variables, that are measureable and quantifiable to characterize the effects on the area of interest.

The recommendations for soil quality are in the same mode of thinking; however, they focus on land management practices. Land management practices are driven by local and regional impacts, which is consistent with the other areas. The difference is that land management practices for soil quality associate strongly with existing metrics, which limits the utility of the second step listed above. Rather, the second step in the development of the soil quality framework is to determine how the evaluation of land management practices is to be aggregated. For instance, the framework may include the development of a single soil sustainability index or the land management practices could be considered separately. In either case, the spirit of the second step is to provide an analytical solution to evaluate the impacts of transportation fuels on soil quality.

It is difficult for TIAX to conclude what the relationship between the two steps for each area will be without actually developing the framework. However, as the framework is developed, the authors are confident that the appropriate combination of these two steps will be apparent. Generally, the following factors must be considered for each area of impact:

1. **Develop baseline activities for each area of impact.** On what common basis can fuel production activities be compared?
2. **Determine temporal and spatial boundary conditions for each area of impact along the entire fuel pathway.** What components of the fuel pathway are included in the assessment of sustainability impacts?
3. **Establish inventory of data to evaluate effects of fuel production pathways.** What are the practices relevant to the fuel pathway and how do they affect each area of sustainability?

4. **Determine weighting factors for evaluation purposes.** To what degree does each pathway affect sustainability, in terms of measurable metrics, value judgments, and policy goals?

Combined, these steps will move the analytical framework for sustainability toward a robust and useful evaluation tool that reflects key sustainability goals.

Water Resources

There is a high level of understanding of the water consumption requirements of transportation fuels, particularly at the farm level, where they are most important. These data, however, must be integrated with local and regional conditions, such as water availability, water pricing, and crop substitution. Ultimately, these local and regional conditions will drive the determination of water impacts over the transportation fuel production pathway. Furthermore, the authors consider it prohibitively challenging to develop a single metric that captures the impact of transportation fuel production pathways on water resources. In fact, to do so may leave out crucial information that could lead to unsustainable choices.

The twofold approach for water resources and next steps include the following:

1. **Determine local/regional water stress indices**. The Energy Commission should become familiar with the WaterGAP2 model, including its strengths, limitations, and ongoing development. There may also be other water stress indices used by local and state water agencies in California or around the United States, particularly in other states with high agricultural outputs.
2. **Use a GREET-type format/model to track other variables and parameters** such as: water requirements, crop type, local/regional climate conditions, soil type, soil quality, and water cooling requirements. This accounting has been done in many of the studies reviewed in this section. The agreement between the various studies indicates that there is a relatively robust methodology in place to account for the water use, including reliable data sources. With so many studies published in the publicly available literature, it should not be difficult to identify the most valuable data sources.

Water Quality

As in the case of water consumption, the knowledge base for the impacts of farm production practices and refinery processes on water quality is solid. However, the data requirements to develop an analytical framework to evaluate transportation fuels are intense. The extensive knowledge base for water quality impacts from various fuel production processes must be coupled with a local or regional watershed modeling effort. This effort, however, may be prohibitively time- or resource-intensive. As an alternative, the Energy Commission could investigate the utility of coupling the water pollutant use with water quality indicators to get a better understanding of the potentially sensitive areas in California, and beyond, which would lead to unhealthy and unsustainable water quality impacts.

1. **Characterize the local and regional issues of water quality**. The authors present two suggestions or recommendations to complete this step.

a. In the first option, the authors refer to a guidance document for the development of site-specific water quality objectives published by the California State Water Resources Control Board(SWRCB 2003). There are similar resources available at the federal level from the EPA.

b. The other option is to perform local and regional watershed modeling. This option is likely more intensive, but probably more rigorous and robust. This option is analogous, for instance, to air shed modeling that is performed in air quality studies.

2. **Account for pollutant discharge at each stage of production using a GREET-type format/tool**, which would be aggregated and reported on a per-unit-energy-of-fuel basis. Pollutants to consider include fertilizers and pesticides, herbicides, or fungicides for farm production; total dissolved solids and other refining effluent. Fertilizer application rates, for instance, are known and are included in the existing GREET model. There is ongoing research at the national laboratories regarding the energy-water nexus, with a focus on the water requirements of various industrial processes, including, but not limited to, power generation. These pollutants should be accounted for based on factors such as crop type, soil type, climatic conditions, and technology type. More specifically, Sandia National Laboratory has developed an energy/water model for internal use that could provide valuable information for this task if made publicly available. Regional and state water agencies could also be useful in this task, as they provide discharge permits and set thresholds based on the type of activity at an industrial facility.

Soil Quality

The existing knowledge base for soil quality and land management practices through academic research and actual practice is strong. Specific additional research is likely not needed to bridge soil quality and the analytical framework. However, much work remains to be done in making decisions regarding the relative value of the various soil quality parameters in evaluating sustainability.

While this framework lays out the elements of a soil quality sustainability index, it does not provide weighting factors for the elements. Because these weighting factors are inherently based on value judgments, either from policy or the evaluator or both, this framework sets only the groundwork for building an analysis tool that incorporates weighting factors appropriate to the purpose of the sustainability assessment. Furthermore, development of this framework into an analysis tool may require adding to, modifying, or simplifying the set of land management practices, keeping in mind that a streamlined and transparent tool is more likely to be used successfully. As such, this framework provides a starting point for stakeholders to discuss the applicability of such a tool to their goals and activities of interest. The next step is to align policy goals with the existing soil quality knowledge base by testing the robustness of this framework under real world considerations.

With these considerations for continued development of an analytical framework in mind, the authors recommend the following two-step approach:

1. **Identify the most pertinent land management practices that reflect impacts on soil quality.** An analytical framework based on land management practices reflects the relationship between an activity and its effects on soil quality indicators without requiring the direct and ongoing comparison of soil sample measurements. The aim of this framework is to distill out the key drivers of soil quality; even if a particular metric is not specifically addressed, its role in soil quality should be captured and indirectly represented by the set of land management practices. This list of land management practices in Table 5 forms the basis of the framework for evaluating the soil quality sustainability of transportation fuel production activities.
2. **Develop a composite index based on land management practices.** To use the framework, the evaluator determines how the activity applies to each of the parameters identified in Table 4. The individual scales from the parameters can then be assessed separately or aggregated into a soil quality index for comparison with other activities. An index would essentially apply numerical scores to the scales (as percentages, absolute numbers, or number of practices selected from the checklist) then apply weighting factors to the parameters to arrive at a final score.

Biodiversity

The existing knowledge base for biodiversity, as it is affected by fuel production, is the weakest of all the areas of impact in this report. The emphasis on biodiversity is based solely on the assumption that biodiversity is important. In other words, there is a binary choice: a high level of biodiversity is good, whereas low-to-no biodiversity is bad. Furthermore, biodiversity is extremely complex and is a function of many variables, including, but not limited to, the other areas of impact considered in this report, i.e., water use, water quality, and soil quality. Biodiversity is an active area of research; yet there is still not a clear connection between biodiversity and ecological function. Despite the complexity of the task and data limitations, the importance of preserving biodiversity is without question. To develop an analytical framework to evaluate the sustainability of transportation fuels without considering biodiversity would be a gross oversight.

The authors recommend the twofold approach, similar to the one proposed for water resources and water quality, for biodiversity.

1. **Determine an appropriate composite of biodiversity indices**. As stated previously, raw data for biodiversity indices are available from various sources (e.g., NatureServe, the Global Biodiveristy Information Facility, the U.S. Fish and Wildlife Service Threatened and Endangered Species Database System, or the California Natural Diversity Database). It is important to reiterate that a composite of indices is required for this step to be relevant. A single metric of biodiversity will not accurately capture the risk posed to a particular region or habitat. More so than other areas, this task should be done in close collaboration with experts in the field to ensure that the results are applicable and reflective of the current understanding of biodiversity.

2. **Define and characterize variables that impact biodiversity and account for these variables along the entire fuel production pathway.** This task is as much about biodiversity as it is other environmental impacts. This step will require considerable comparison between various metrics to demonstrate how they impact or correlate with biodiversity and how they correlate with each other. For instance, the work by Pfister et al. (2009) where they use NPP as a proxy for biodiversity based on a correlation between NPP and VPBD is an interesting example that requires further investigation. Similarly, the Eco-indicator 99 model should provide similarly useful guidance in this task.

In addition to developing an analytical framework to include biodiversity, further research will bridge the gap between biodiversity and its relationship to the effects on the full transportation fuel cycle. This could involve, for instance, detailed surveys (addressing the indicators listed above) of an environment for multiple years (not drawing from old archival observations) before the installation of a fuel production facility and multiple years after installation to develop averaged baseline and impact to the species, abundance, and its changes over time is required. Furthermore, the analytical framework should be adaptable so as to allow for research advances to be incorporated into the framework. Most notably, as the connection between biodiversity and ecological system function improves, the first step in the framework can be modified.

Ultimately, the authors conclude that the development of an analytical framework to incorporate other environmental sustainability factors considered in this report will be an extremely challenging and intensive undertaking for the Energy Commission. There is a considerable amount of data available in each of the areas of impacts; however, these data are not necessarily aggregated in a way that will be immediately useful. Furthermore, most of the impacts and metrics that have been developed in the literature provide an overview of the issue, rather than a rigorous analysis of all the details that must be worked out for a sound analytical framework. Similarly, TIAX cautions against the development of a single metric for any of the environmental sustainability concerns addressed in this report. It is short-sighted to assume that the straightforward metric of choice for GHG emissions from the fuel production pathway, g CO_2-eq/MJ, can simply be altered for other areas of impact. If nothing else, the authors' research indicates that the other areas of sustainability are driven primarily by local and regional conditions, unlike greenhouse gas emissions, which can be treated uniformly across time (for the most part) and space.

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Glossary

AB 1007	Assembly Bill 1007 – California State Alternative Fuels Plan
AB 118	Assembly Bill 118 – Alternative and Renewable Fuel and Vehicle Technology Act
AB 32	Assembly Bill 32 – Global Warming Solution Act (2006)
CBD	Convention on Biodiversity
CDFG	California Department of Fish and Game
CEQA	California Environmental Quality Act
CH4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO2	carbon dioxide
CSS	cyclic steam simulation
EA	Environmental assessment
EIR	Environmental impact report
EIS	Environmental impact statement
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate model
ET	evapotranspiration
FCV	fuel cell vehicle
GHG	greenhouse gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GWP	global warming potential
HFC	hydro fluorocarbons
IDB	Inter-Development Bank
LCFS	Low Carbon Fuel Standard
L-THIA	Long-Term Hydrological Impact Assessment
MTBE	methyl t-butyl ether
N	nitrogen (fertilizer)
N2O	nitrous oxide
ND	Negative declaration
NEPA	National Environmental Protection Act
NLEAP	Nitrate Leaching and Economic Analysis Package
NOx	nitrogen oxide
NPP	net primary production
P	phosphorous (fertilizer)
PDF	partially depleted fraction
PM10	particulate matter, <10 μm
PM2.5	particulate matter, <2.5 μm

RSB	Roundtable on Sustainable Biofuels
RUSLE2	Revised Universal Soil Loss Equation, version 2
SAGD	steam assisted gravity drainage
SMAF	Soil Management Assessment Framework
SOx	sulfur oxide
SSI	soil sustainability index
SWET	Soil and Water Evapotranspiration Tool
UNEP	United Nations Environmental Program
USDA	United State Department of Agriculture
USFWS	United States Fish and Wildlife Service
VMT	vehicle miles traveled
VOC	volatile organic compounds
VPBD	vascular plant biodiversity
WEPP	Water Erosion Prediction Project
WF	water footprint
WUE	water use efficiency
ZEV	zero emissions vehicle